NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 904

ESTIMATION OF F-3 AND F-4 KNOCK-LIMITED PERFORMANCE RATINGS FOR TERNARY AND QUATERNARY BLENDS CONTAINING TRIPTANE OR OTHER HIGH-ANTIKNOCK AVIATION-FUEL BLENDING AGENTS

By HENRY C. BARNETT

1948

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	{kilometers per hour {meters per second	kph mps	miles per hour feet per second	mph fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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By Henry C. Barnett

SUMMARY

Charts are presented that permit the estimation of F-3 and F-4 knock-limited performance ratings for certain ternary and quaternary fuel blends. Ratings for various ternary and quarternary blends estimated from these charts compare favorably with experimental F-3 and F-4 ratings. Because of the unusual behavior of some of the aromatic blends in the F-3 engine, the charts for aromatic-paraffinic blends are probably less accurate than the charts for purely paraffinic blends.

INTRODUCTION

An investigation of the knock-limited performance of triptane and other high-antiknock components of aviation fuels was conducted at the NACA Cleveland laboratory in the F-3 and the F-4 rating engines (reference 1). The data of reference 1 are presented herein in the form of charts, which can be used to estimate the F-3 and the F-4 antiknock ratings for multicomponent blends of the various fuels investigated.

The F-4 data appearing in these charts are based on the following blending equation suggested in reference 2 for supercharged-engine data:

$$\frac{1}{\text{imep}}=\frac{N_1}{(\text{imep})_1}+\frac{N_2}{(\text{imep})_2}+\frac{N_3}{(\text{imep})_3}+\cdots \qquad (1)$$

where

imep	knock-limited indicated mean effective pressure of fuel blend
$(\text{imep})_1$, $(\text{imep})_2$, $(\text{imep})_3$, . . .	knock-limited indicated mean effective pressure of components 1, 2, 3, . . .
N_1, N_2, N_3, . . .	mass fractions of components 1, 2, 3, . . . in fuel blend

Equation (1) has been satisfactory for blends in which all components are paraffinic and have equal concentrations of tetraethyl lead. The equation applies most generally when the experimental data are taken at high fuel-air ratios. With the exception of data for one fuel in the present analysis, all the F-4 knock-limited performance data are considered at a fuel-air ratio of 0.11.

The analysis of F-3 data presented herein is strictly empirical but has been found to agree satisfactorily in most cases with the experimental data. The accuracy of the performance charts presented was checked by testing prepared blends under F-3 and F-4 conditions and comparing the observed ratings with those predicted from the charts.

EXPERIMENTAL DATA

The experimental results upon which this analysis is based are presented in table I (reproduced from reference 1). No performance numbers in this table greater than 161 were used in this analysis, as will be indicated later. The performance numbers for the F-4 tests were estimated from a reference-fuel framework (reference 1) consisting of knock-limited performance curves for 90-percent S-3 reference fuel plus 10-percent M-4 reference fuel and for S-3 reference fuel clear and with 0.5, 1.25, 2, 4, and 6 ml TEL per gallon.

The use of this method of rating instead of the usual procedure of direct matching was necessary because of the extensive nature of the program; complete mixture-response curves for 132 blends were obtained. For this reason, the accuracy of the performance numbers shown in table I for F-4 ratings is largely dependent on the day-to-day reproducibility of the engine. The brief analysis of the results given in reference 1 indicates that this reproducibility is good at high fuel-air ratios. Inasmuch as the analysis herein is concerned only with data at a fuel-air ratio of 0.11, it is believed that the performance-number ratings at this fuel-air ratio are reasonably accurate.

All blends investigated were prepared on a volume basis.

PREPARATION OF PERFORMANCE CHARTS

In order to make the final charts useful for the prediction of blends giving F-4 performance numbers greater than 161 at a fuel-air ratio of 0.11, it was considered desirable to extrapolate the performance curve to at least a performance number of 200. This extrapolation was made by plotting the performance numbers against knock-limited indicated mean effective pressure from the reference-fuel framework in reference 1. (See fig. 1.) Although there is a definite break in this curve at a performance number of 130, the curve appears to be linear between 130 and 161. On the assumption that this linear relation is true, a straight line was drawn through the points at 130 and 161 and extended to a performance number of 200. The extrapolation between

161 and 200 is shown as a broken line in figure 1. In reference 1, a different method of extrapolation was used for performance numbers greater than 161 (fig. 1); consequently, the performance-number values above 161 in table I for F–4 ratings are not the same as those used in preparing the performance charts in the present report.

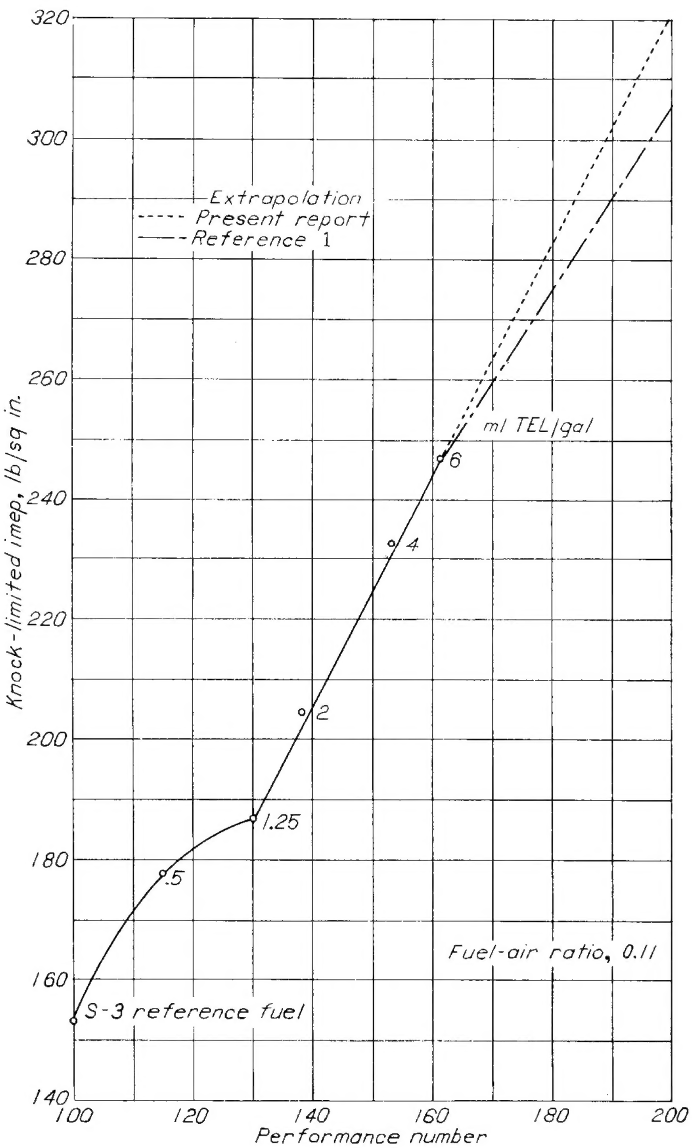


FIGURE 1.—Relation between performance numbers and knock-limited indicated mean effective pressures as determined in F–4 rating engine.

TERNARY BLENDS

As an example of the preparation of a performance chart, first it is desired to know the F–3 and the F–4 performance numbers of all possible ternary blends of hot-acid octane, an aviation alkylate, and a virgin base stock. These three fuels were chosen because their blending relations follow equation (1). A plot of composition against the reciprocal of the knock-limited indicated mean effective pressure for binary blends of any two of these fuels will result in a straight line. The three binary combinations of these materials are shown in figure 2. The ordinate scale of this figure is a reciprocal scale used for convenience in order that the indicated mean effective pressures can be plotted directly. Experimental data for figure 2 were taken from table I.

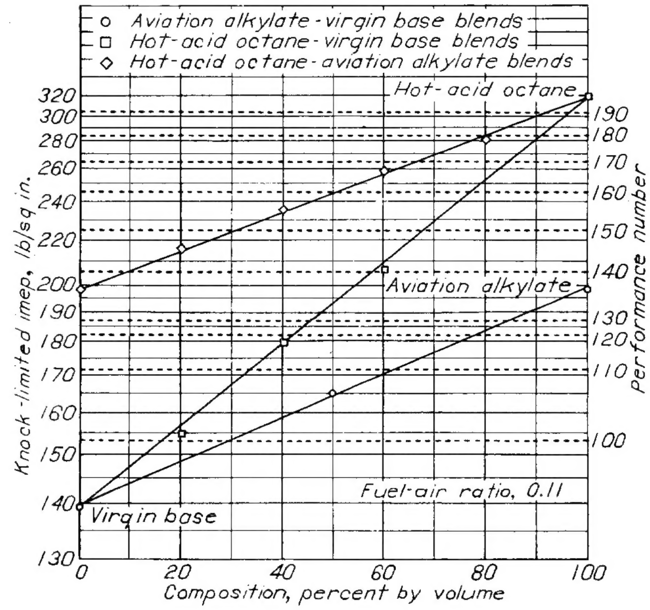


FIGURE 2.—Knock-limited performance determined by F–4 rating method for binary blends of hot-acid octane, aviation alkylate, and virgin base stock. All blends contain 4 ml TEL per gallon.

In the next operation, lines of constant performance number are drawn on the plot (shown as dotted lines, fig. 2). These lines are established by reading values of indicated mean effective pressure at equal increments of performance number in figure 1. The data as shown in figure 2 are the basic information needed to establish F–4 rating lines on the final chart for multicomponent blends.

For convenience in relating composition and knock-limited performance of ternary fuel blends, all performance charts are prepared on triangular coordinate paper. A brief description of the use of triangular coordinate paper is given in the appendix. A more detailed description of triangular plots is given in reference 3.

The performance chart for the system of hot-acid octane, aviation alkylate, and virgin base stock is shown in figure 3. Lines of constant performance number in this figure were determined by noting the intersections of the constant performance lines (fig. 2) with the blending lines. For example, the 150-performance-number line in figure 2 intersects the blending line of hot-acid octane and aviation alkylate at a composition of 32-percent hot-acid octane and 68-percent alkylate and intersects the blending line of hot-acid octane and virgin base stock at a composition of 67-percent hot-acid octane and 33-percent virgin base stock. These two compositions were plotted on figure 3 and joined by a straight line. Any point on this line represents a blend of hot-acid octane, alkylate, and virgin base stock that will give a performance number of 150 in the F–4 engine at a fuel-air ratio of 0.11. All performance lines in figure 3 were established in this manner.

The lines in figure 3 are parallel, which is to be expected when the curves shown in figure 2 are linear. On the basis of data in this report and in references 4 and 5, it appears that most paraffinic fuels blend linearly at high fuel-air ratios. Even though certain constituents such as the aromatics or ethers did not blend linearly with paraffinic base

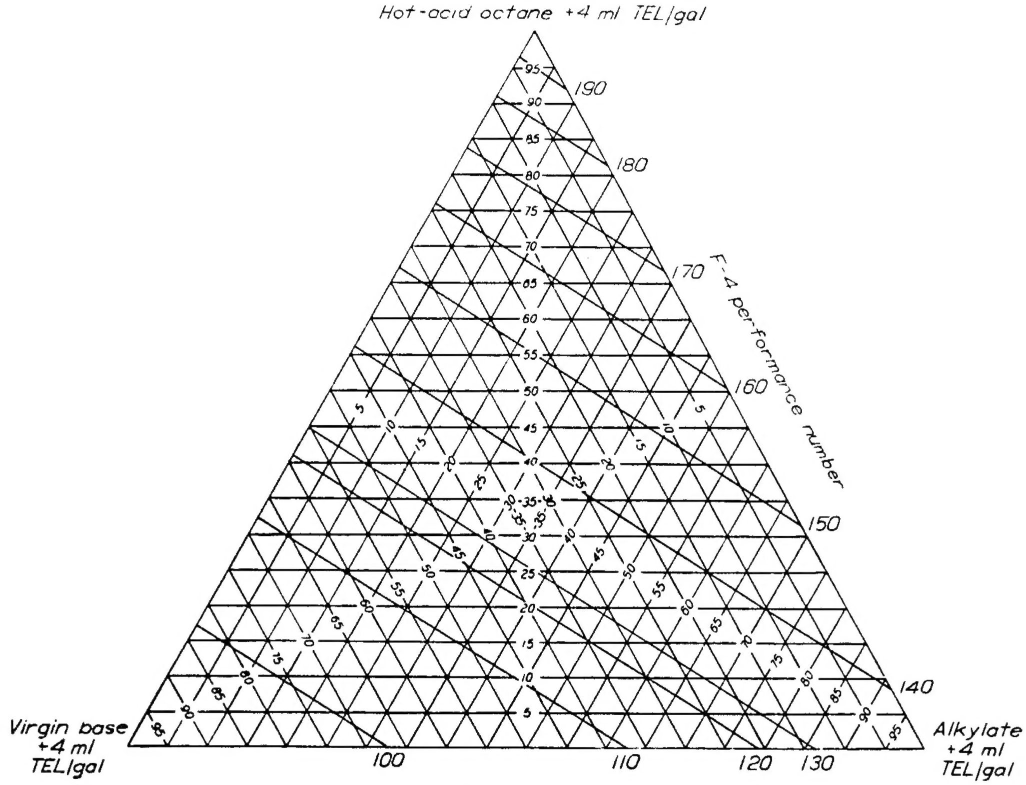


Figure 3.—Knock-limited performance determined by F-4 rating method for ternary blends containing hot-acid octane, aviation alkylate, and virgin base stock. F-4 ratings at fuel-air ratio of 0.11.

fuels, the procedure just outlined for the preparation of performance-number charts is not altered. A nonlinear relation in a plot of the type shown in figure 2 results in a variation of slope with performance number on the final triangular plot.

The procedure used for determining the lines of constant F-3 performance for blends of the same fuels used in preparing figure 3 differs from that used for F-4 performance in that performance numbers are plotted directly against composition on linear coordinate paper and an estimated "best" curve is drawn through the data points to determine the binary blending relations shown in figure 4. There is nothing to justify the use of this empirical method for dealing with F-3 ratings except that the end result agrees reasonably well with the experimental results. One or two exceptions to this method will be pointed out later.

The compositions at the intersections of a given constant performance line with the blending lines (fig. 4) were plotted on triangular coordinate paper and joined by straight lines. The resulting F-3 performance lines are shown in figure 5. The final chart (fig. 6) was obtained by superimposing figure 5 on figure 3. Performance charts for the following fuel constituents blended with aviation alkylate and virgin base stock (all blends leaded to 4 ml TEL/gal) were prepared in the same manner and are presented in figure 7: triptane, diisopropyl, neohexane, isopentane, benzene, cumene, mixed xylenes, toluene, and methyl *tert*-butyl ether. Charts for hot-acid octane, triptane, diisopropyl, neohexane, isopentane,

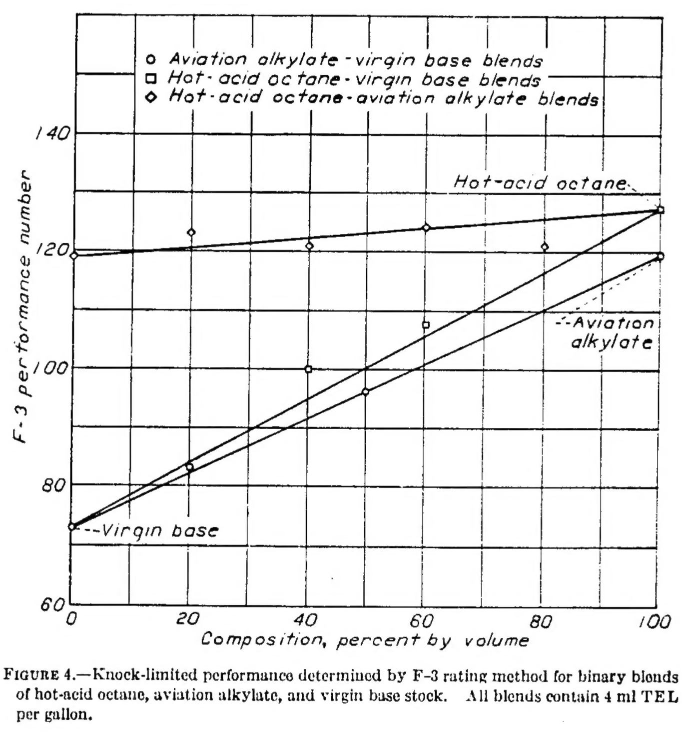


Figure 4.—Knock-limited performance determined by F-3 rating method for binary blends of hot-acid octane, aviation alkylate, and virgin base stock. All blends contain 4 ml TEL per gallon.

benzene, mixed xylenes, toluene, and methyl *tert*-butyl ether blended with aviation alkylate and one-pass catalytic stock are presented in figure 8.

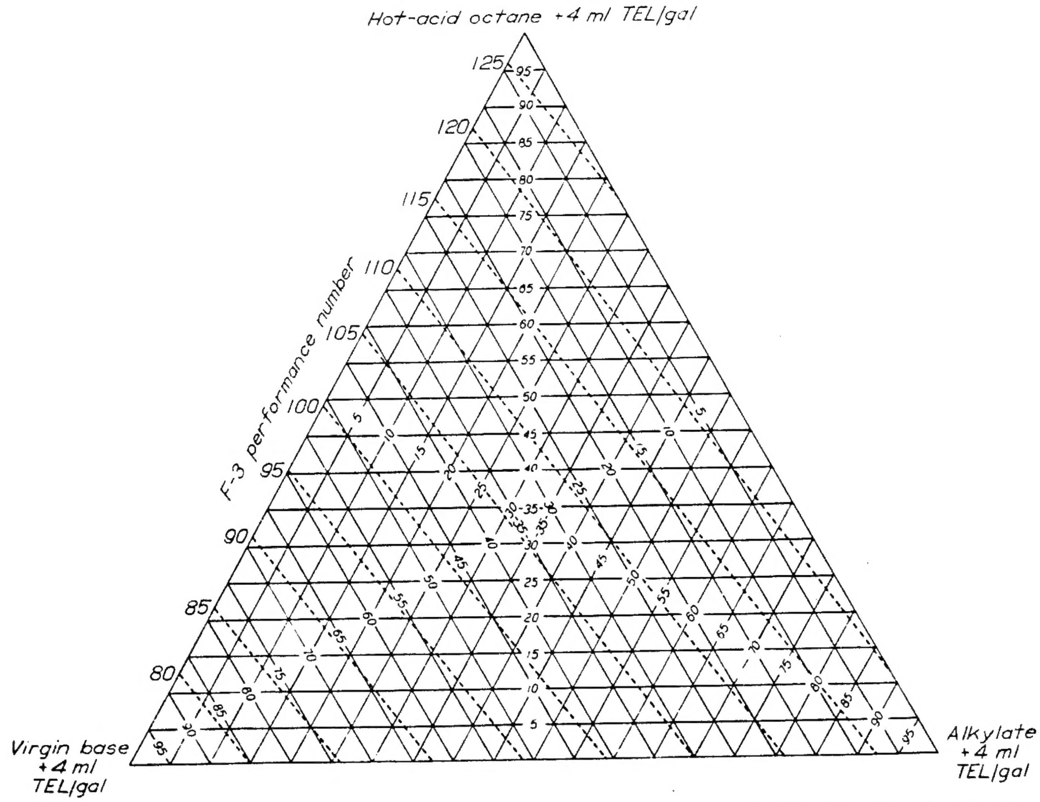


FIGURE 5.—Knock-limited performance determined by F-3 rating method for ternary blends containing hot-acid octane, aviation alkylate, and virgin base stock.

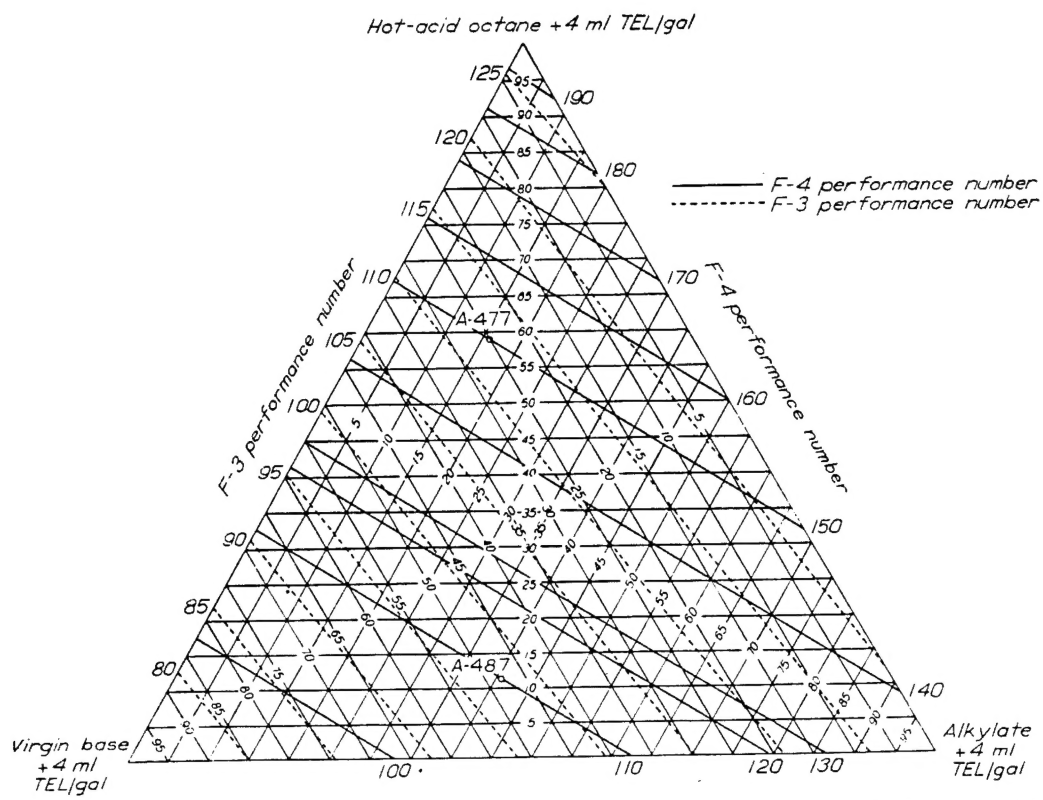
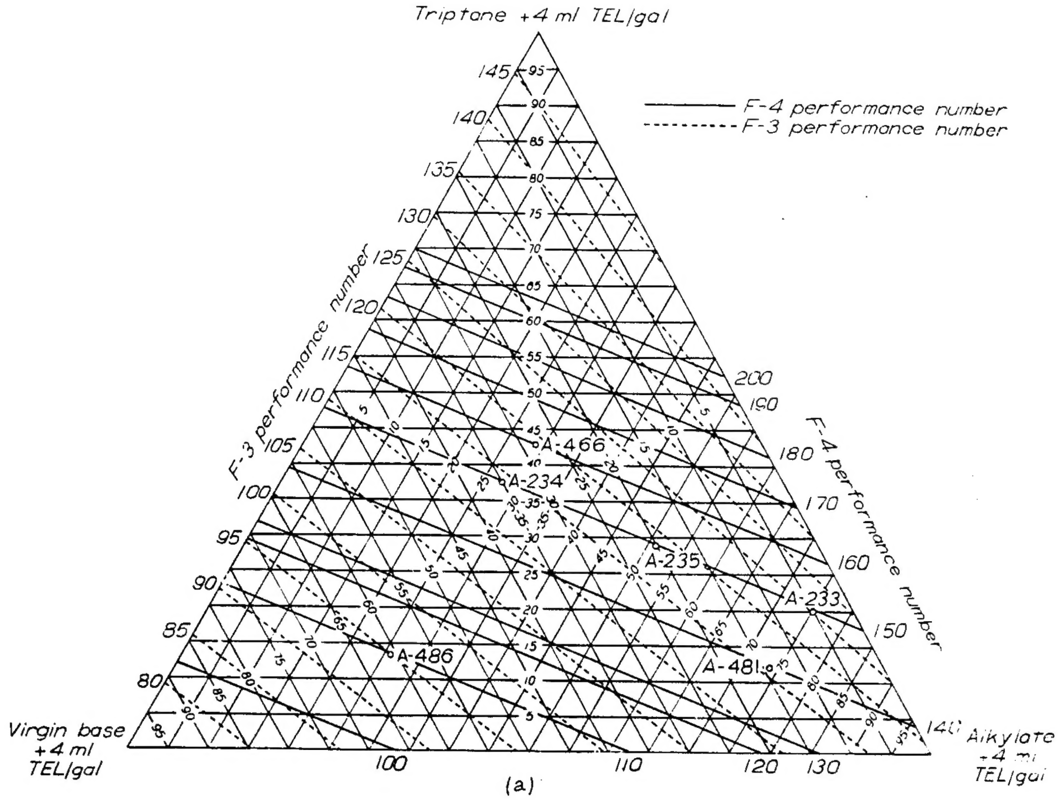
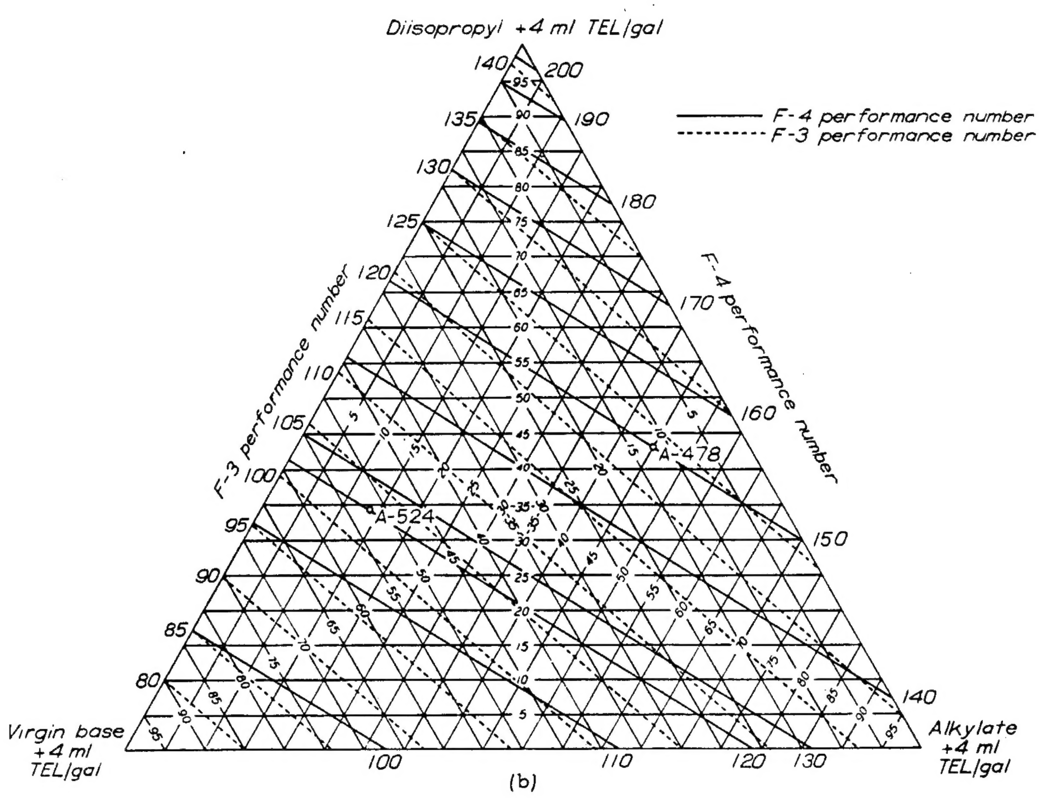


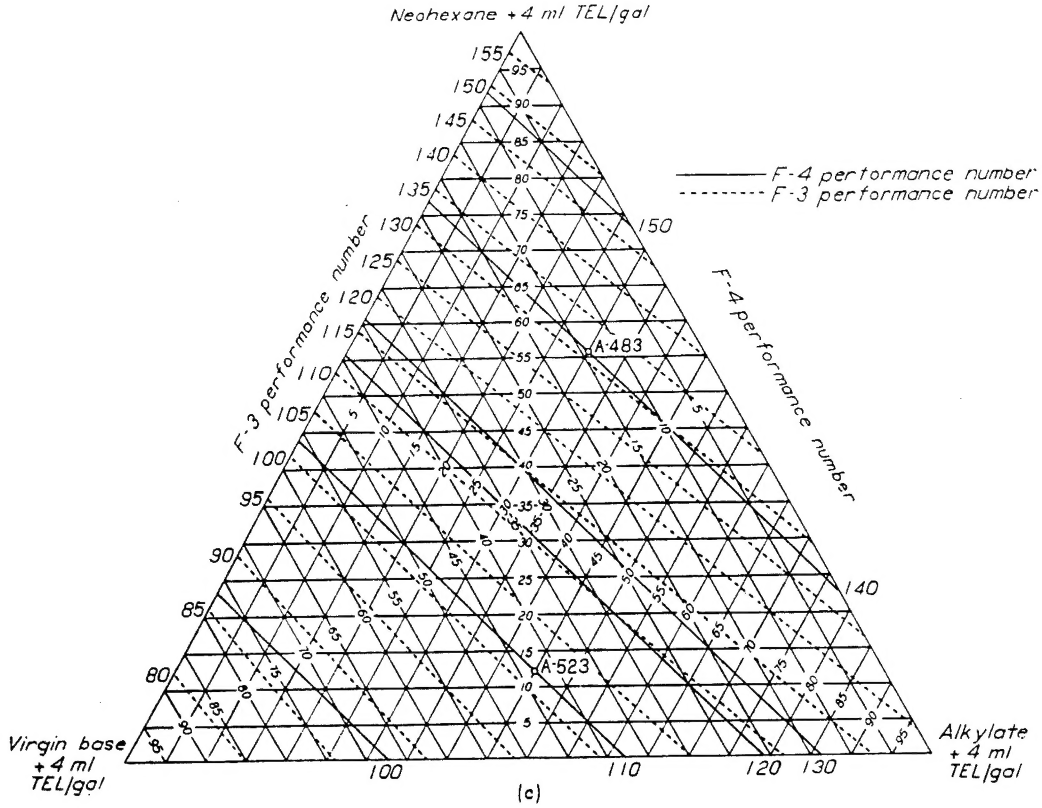
FIGURE 6.—Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing hot-acid octane, aviation alkylate, and virgin base stock. F-4 ratings at fuel-air ratio of 0.11.

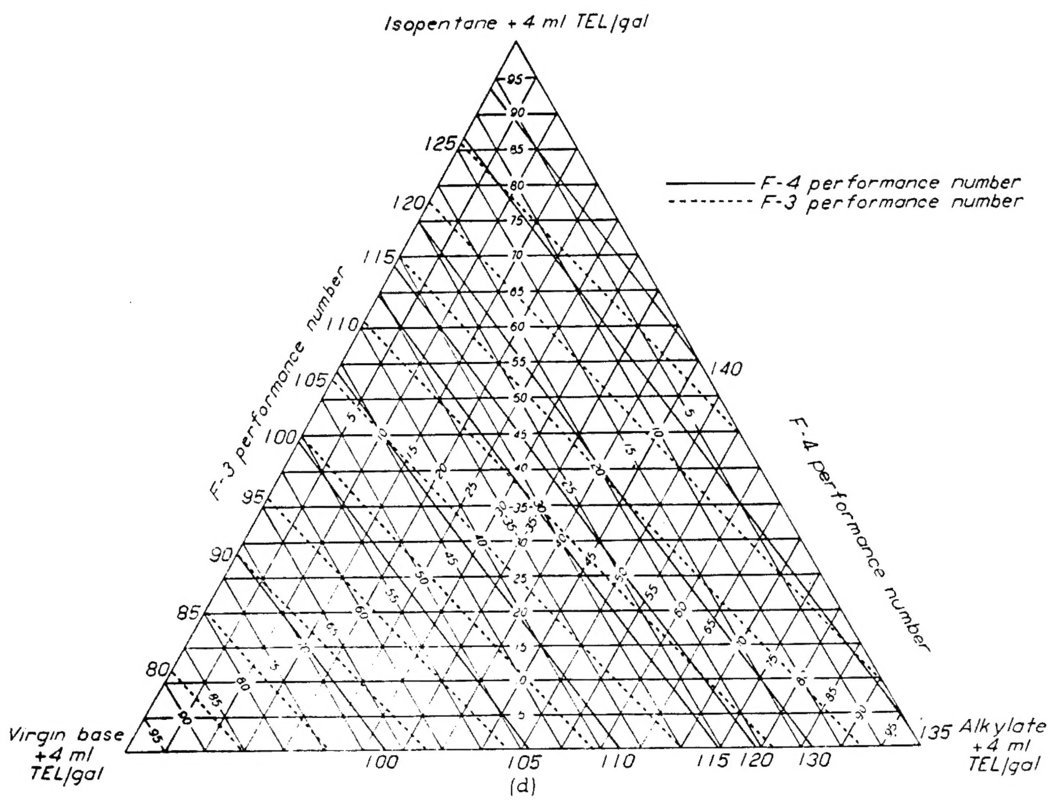




(a) Triptane blends: F-4 ratings at fuel-air ratio of 0.11.
(b) Diisopropyl blends; F-4 ratings at fuel-air ratio of 0.11.

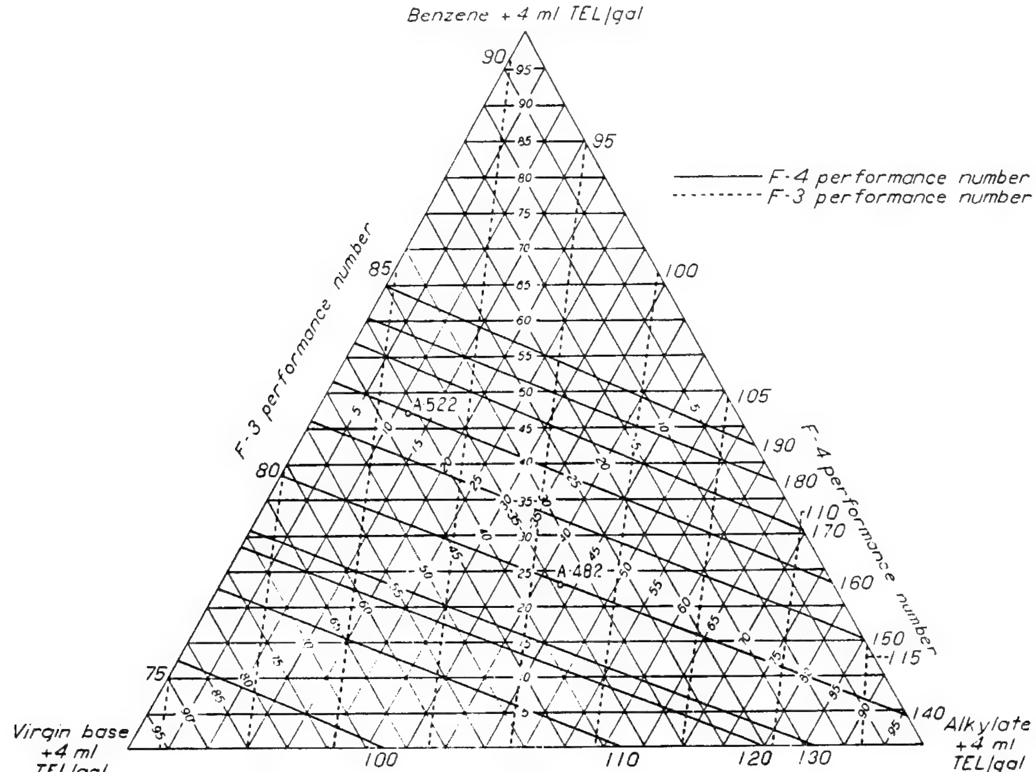
FIGURE 7.—Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and virgin base stock.



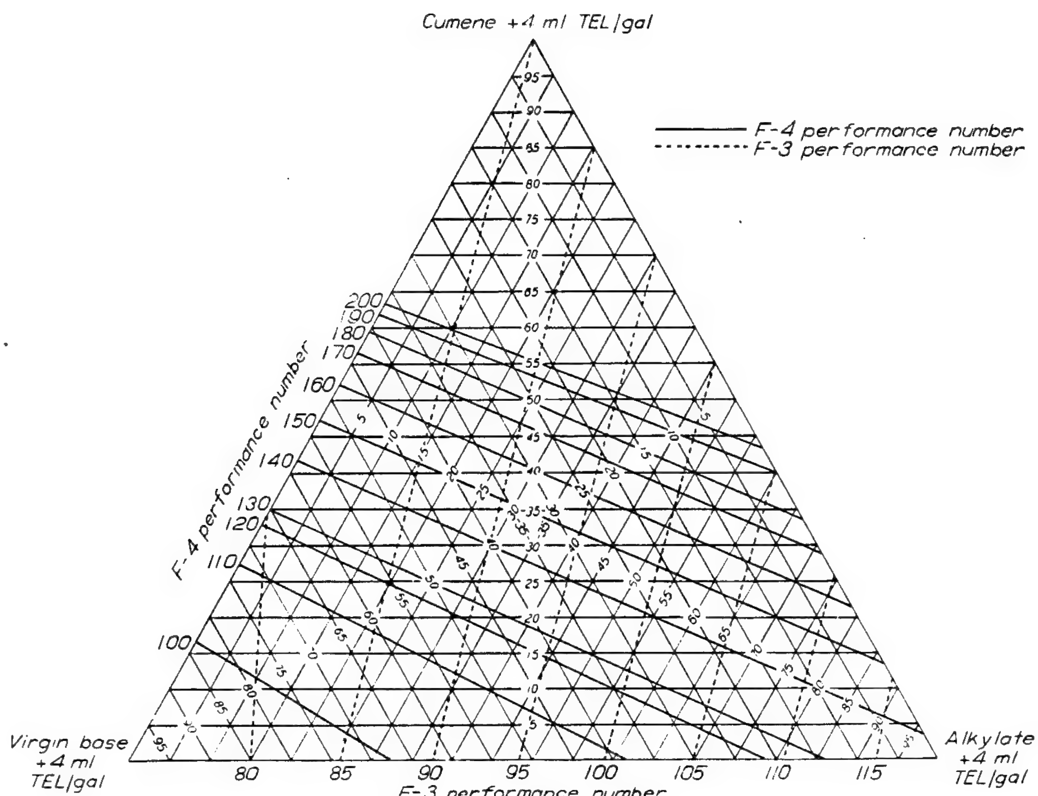


(c) Neohexane blends; F-4 ratings at fuel-air ratio of 0.11.
(d) Isopentane blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 7.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and virgin base stock.



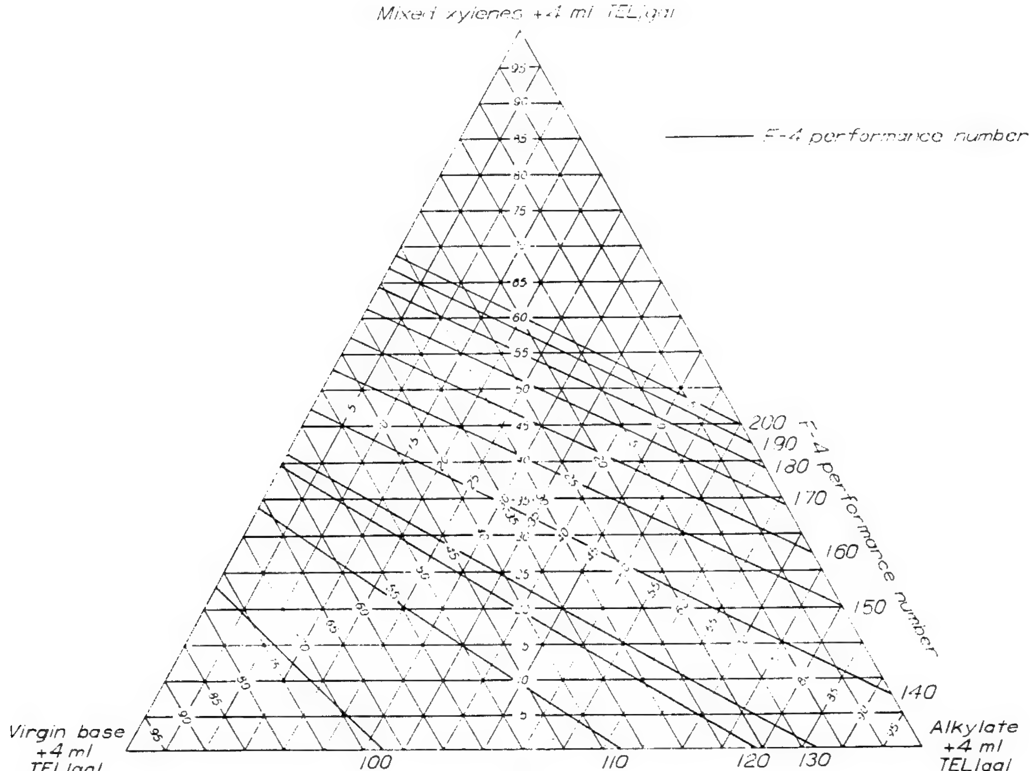
(e)



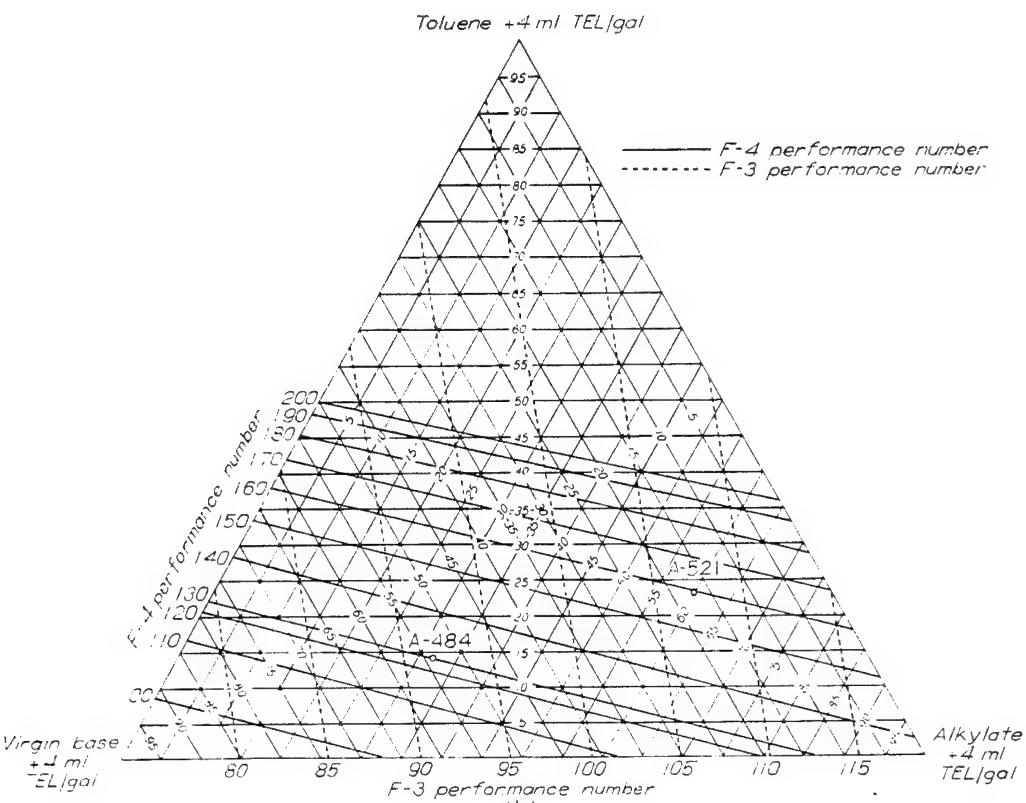
(f)

(e) Benzene blends; F-4 ratings at fuel-air ratio of 0.11.
(f) Cumene blends; F-4 ratings at fuel-air ratio for peak power.

FIGURE 7.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and virgin base stock.



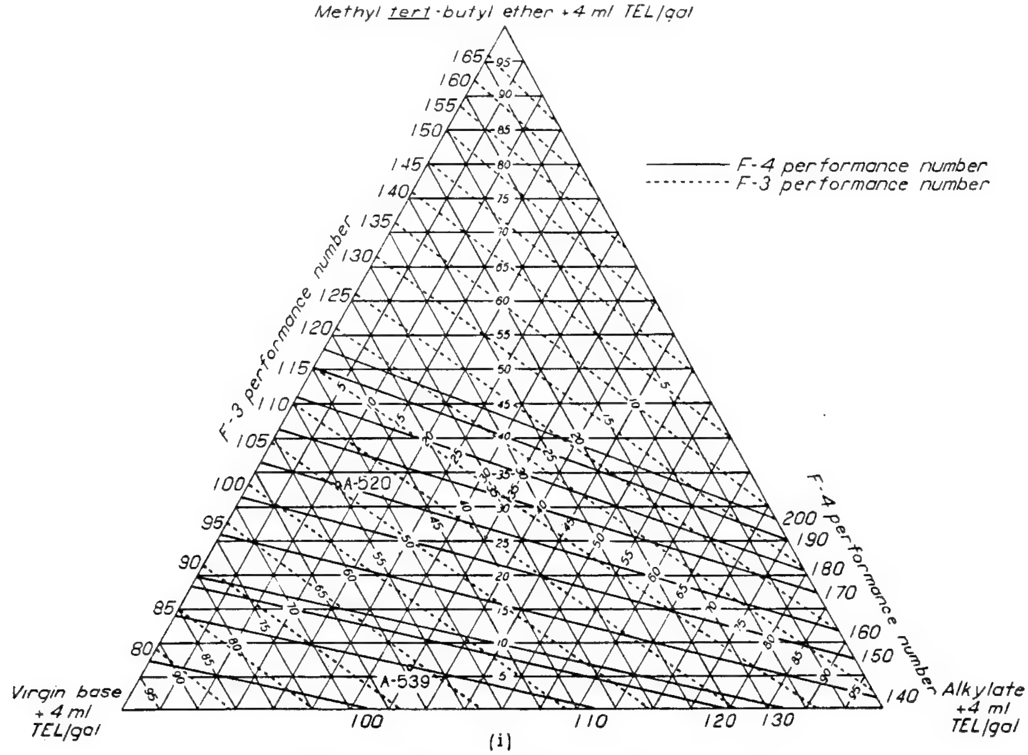
(g)



(h)

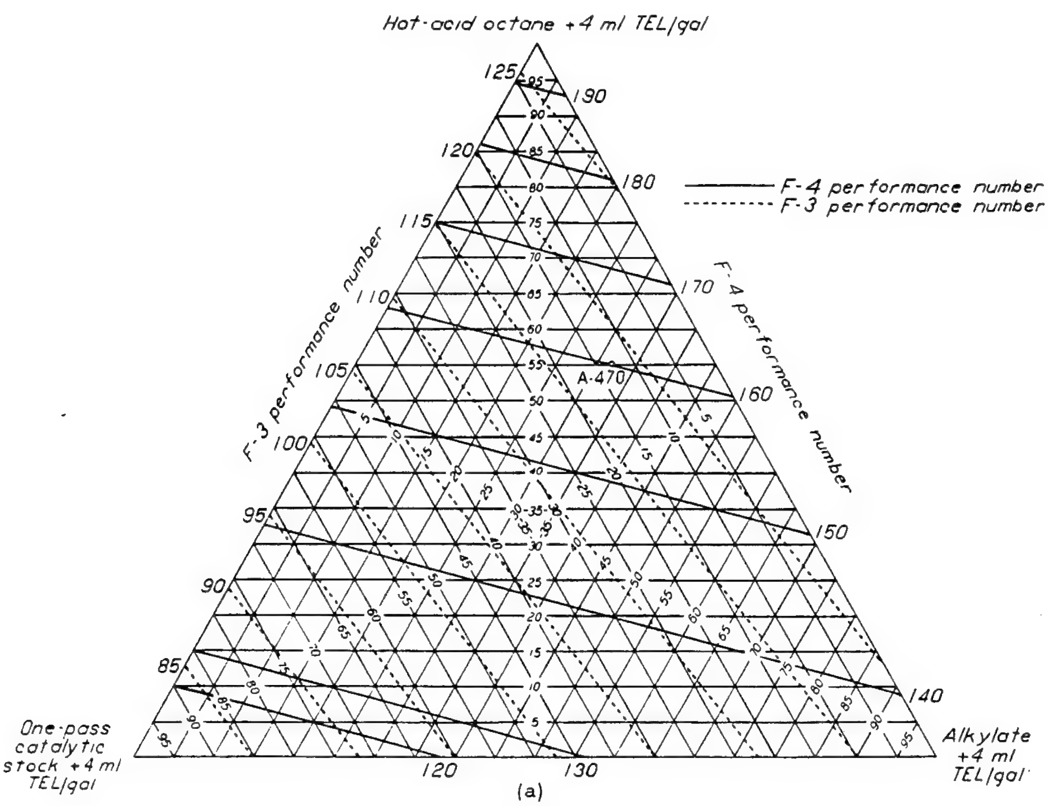
(g) Mixed xylenes blends; F-4 ratings at fuel-air ratio of 0.11.
(h) Toluene blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 7.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and virgin base stock.



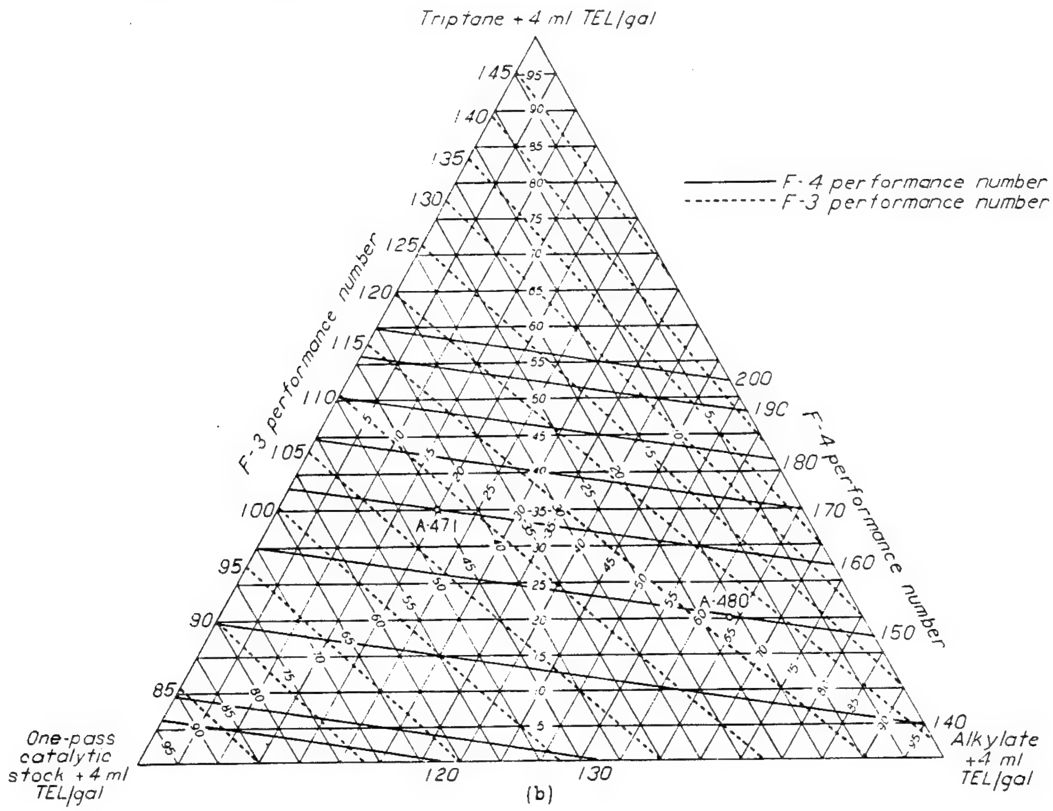
(i) Methyl *tert*-butyl ether blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 7.—Concluded. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and virgin base stock.

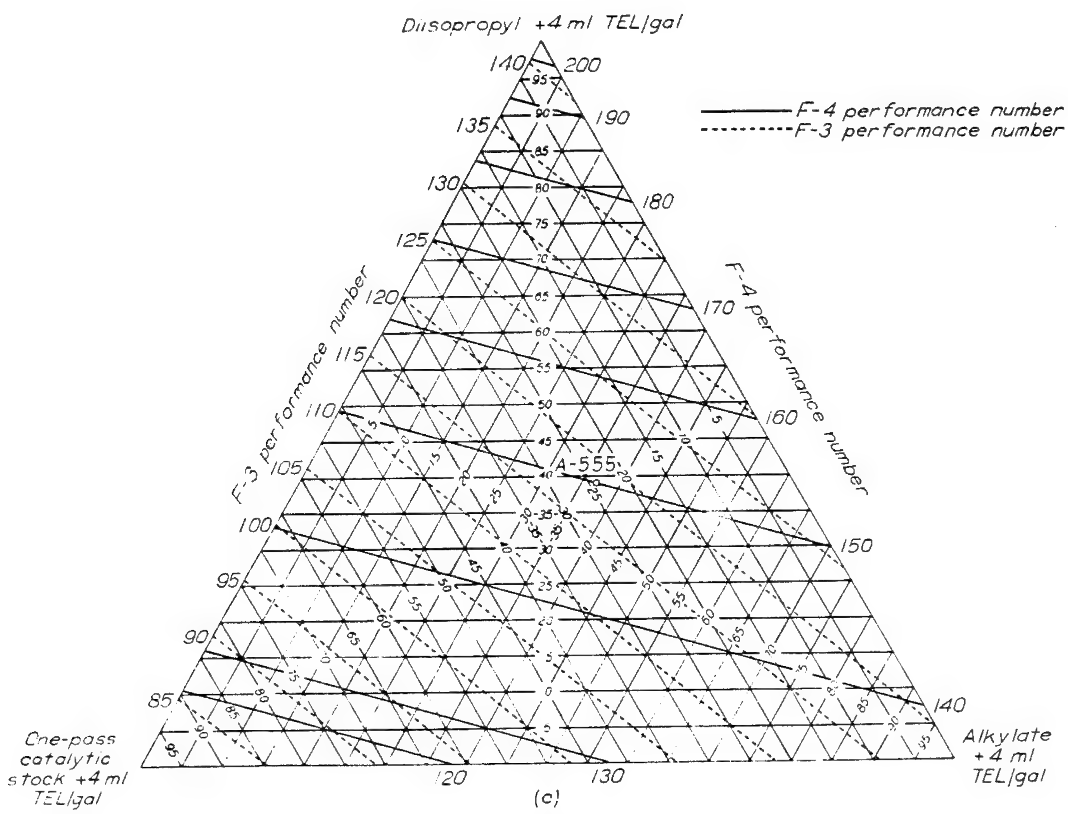


(a) Hot-acid octane blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 8.—Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and one-pass catalytic stock.



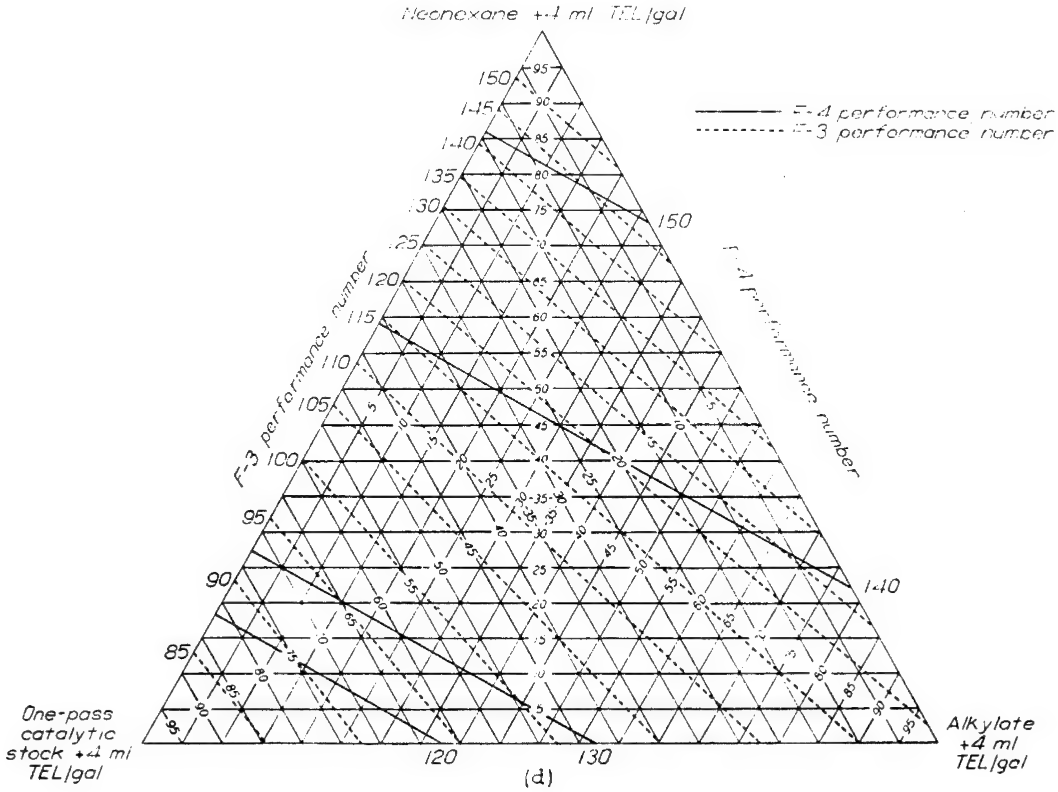
(b)



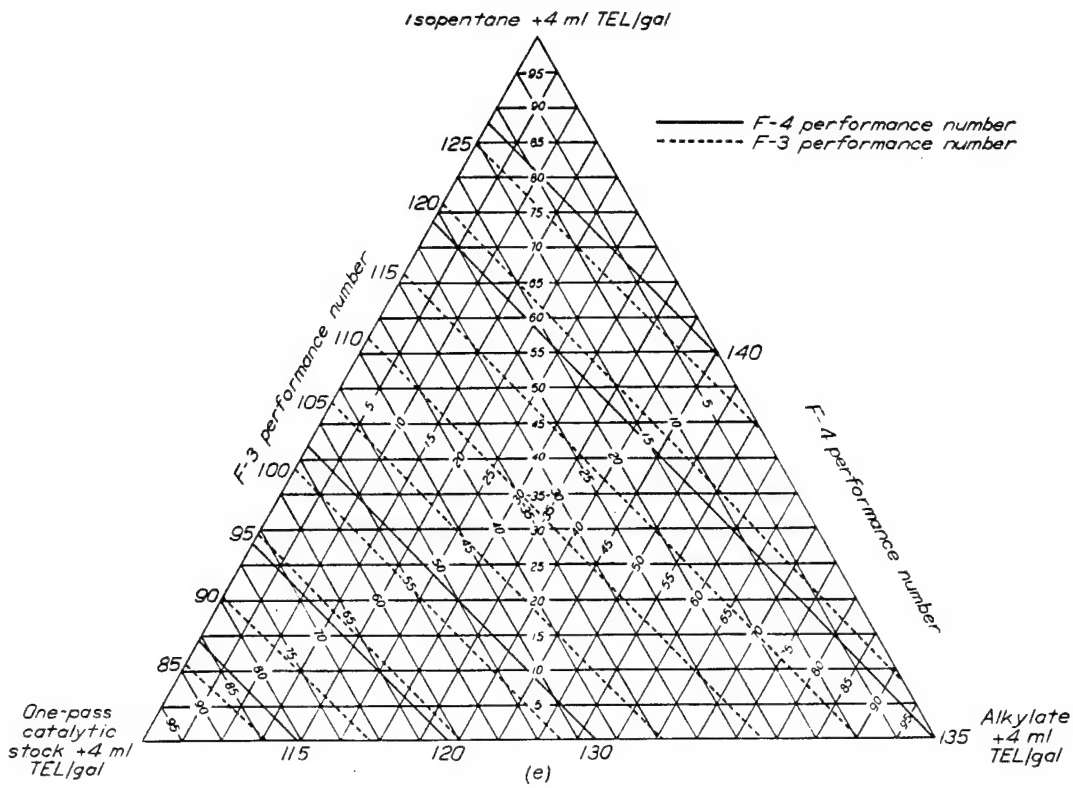
(c)

(b) Triptane blends; F-4 ratings at fuel-air ratio of 0.11.
(c) Diisopropyl blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 8.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and one-pass catalytic stock.



(d)



(e)

(d) Neohexane blends; F-4 ratings at fuel-air ratio of 0.11.
(e) Isopentane blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 8.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and one-pass catalytic stock.

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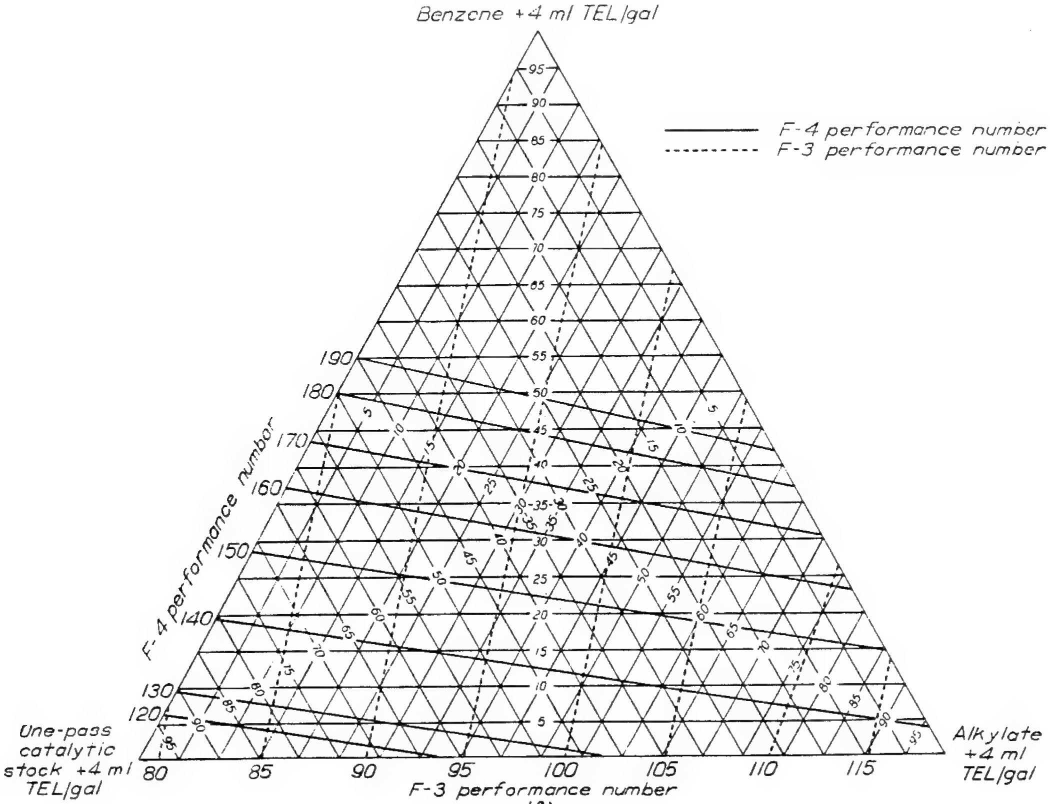
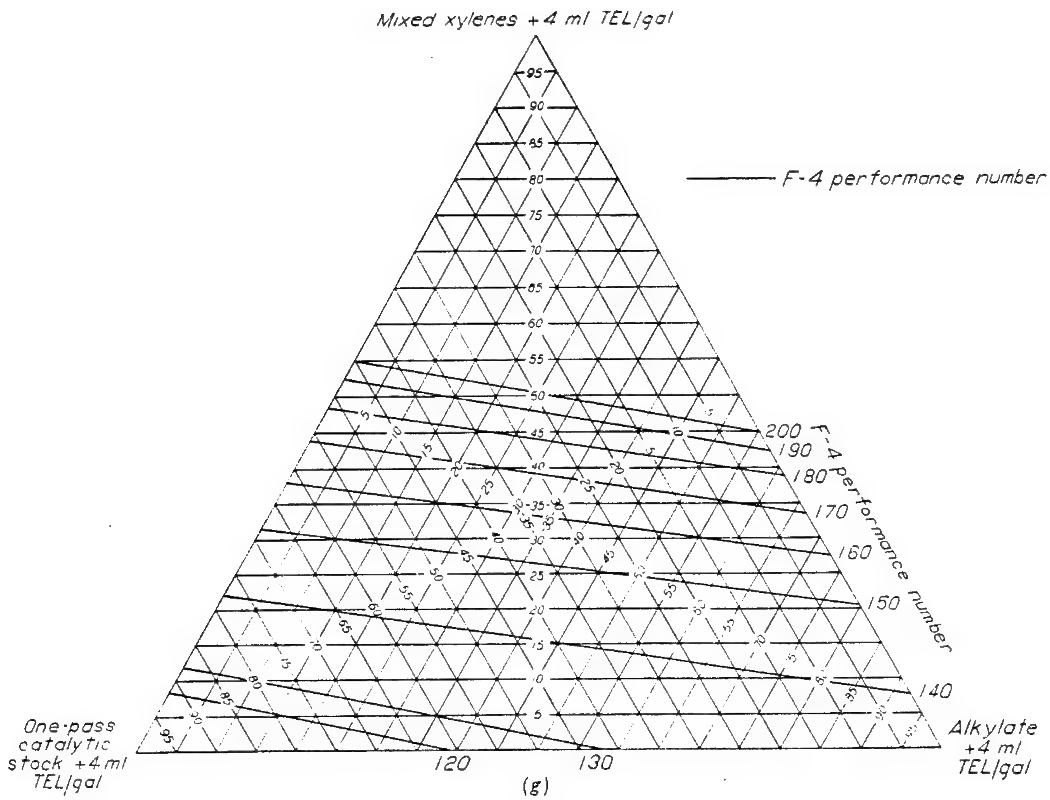


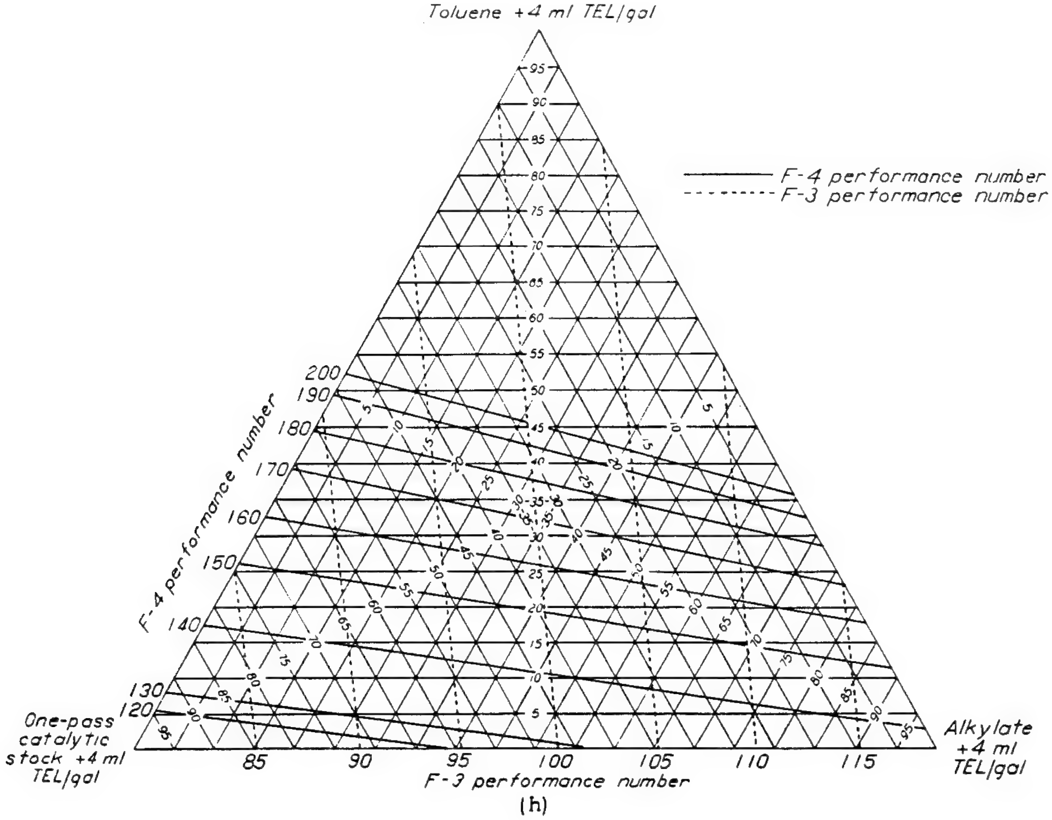
(f)

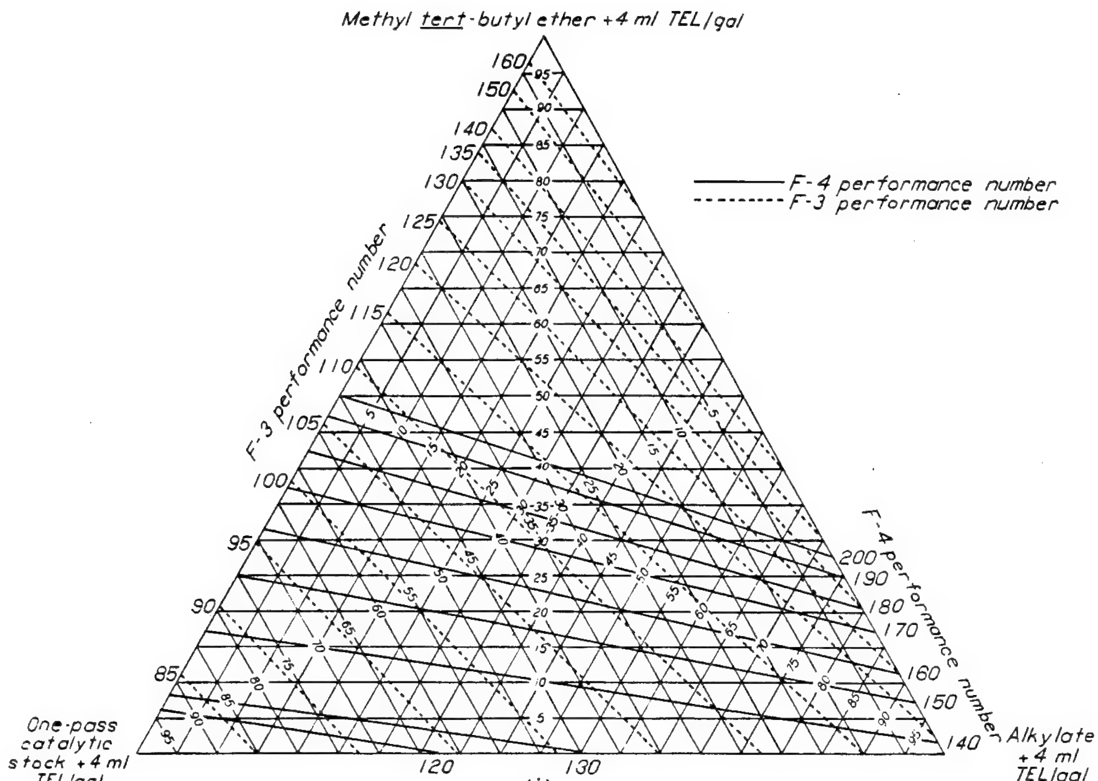


(g)

(f) Benzene blends; F-4 ratings at fuel-air ratio of 0.11.
(g) Mixed xylenes blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 8.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and one-pass catalytic stock.





(h) Toluene blends; F-4 ratings at fuel-air ratio of 0.11.
(i) Methyl *tert*-butyl ether blends; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 8.—Concluded. Knock-limited performance determined by F-3 and F-4 rating methods for ternary blends containing high-antiknock blending agents, aviation alkylate, and one-pass catalytic stock.

In figure 7 (f) the lines showing F–4 performance numbers for cumene blends were determined by plotting peak knock-limited power values rather than power values at a fuel-air ratio of 0.11. This deviation from the procedure used for all other plots in figures 6, 7, and 8 was necessary because most of the mixture-response curves for the cumene blends investigated (reference 1) intersected at fuel-air ratios between 0.10 and 0.11. (See fig. 9.) The fuel-air ratio for peak knock-limited power varied between 0.115 and 0.132 for the cumene blends used in preparing figure 7 (f).

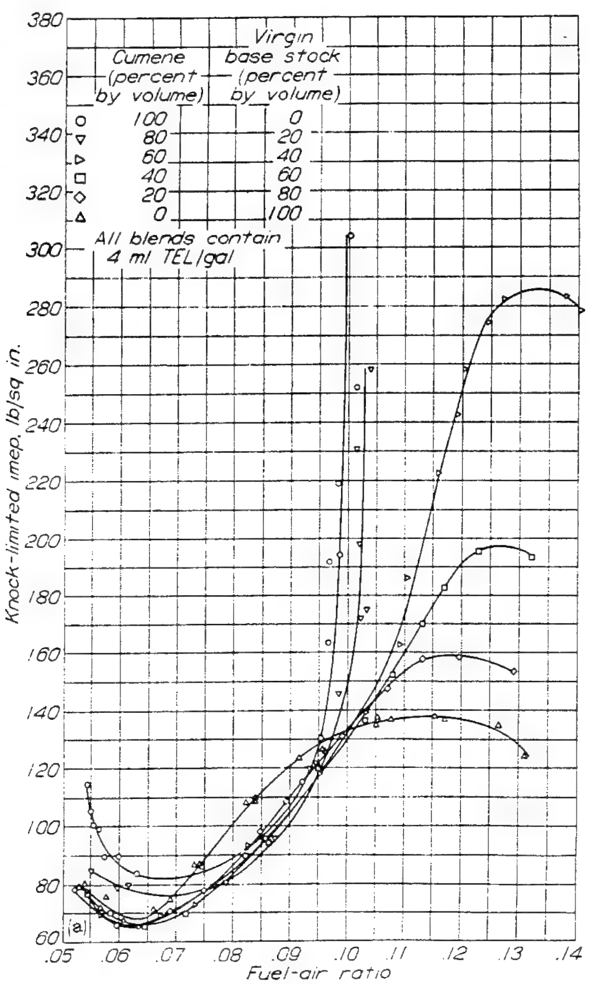
No plot was prepared for blends of cumene, aviation alkylate, and one-pass catalytic stock because rich-mixture peaks were not obtained for a sufficient number of the binary blends of cumene and one-pass catalytic stock reported in reference 1.

Lines of F–3 performance for xylenes blends were not plotted in figures 7 (g) and 8 (g) because the curve of composition against F–3 ratings for binary blends of xylenes and aviation alkylate passed through a minimum. (See fig. 10.)

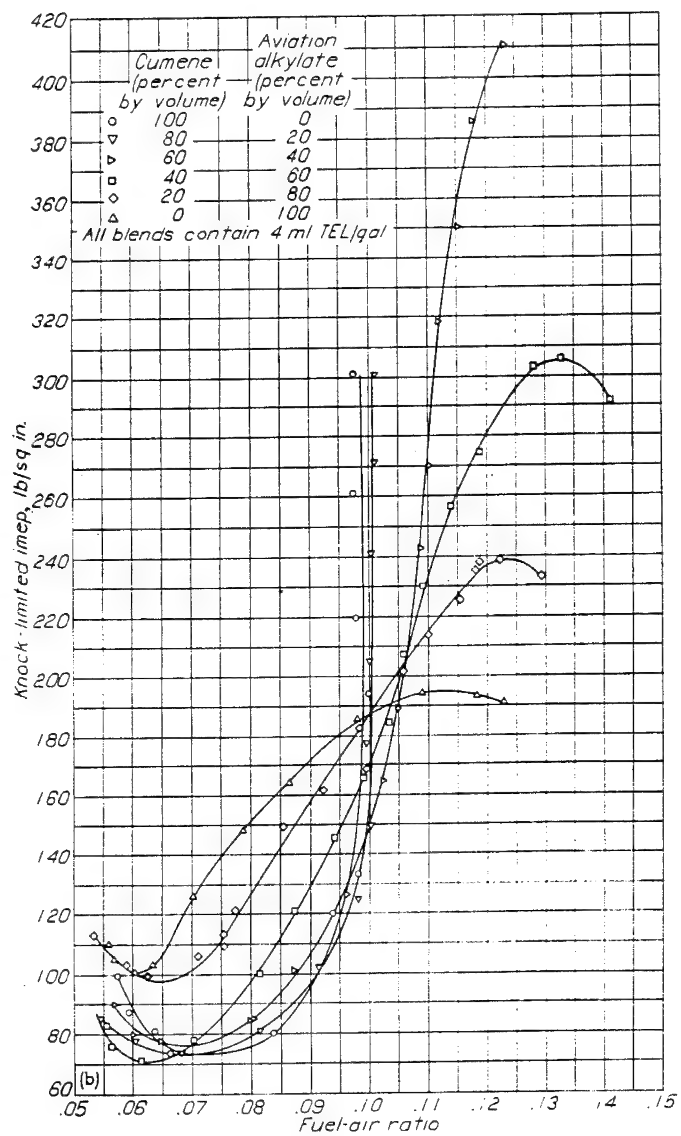
In general, data obtained on the F–3 engine for the aromatic blends could not be handled with complete satisfaction by the empirical procedure previously explained. For this reason, the accuracy of the lines of constant F–3 performance shown for the aromatic-paraffinic systems in figures 7 and 8 is questionable.

QUATERNARY BLENDS

The performance charts presented in figures 6, 7, and 8 are of interest primarily from considerations of maxmium knock-limited performance attainable with various combinations of fuel blending agents and current base stocks. The producers of aviation fuel, however, are interested in the maximum knock-free power attainable with a finished blend that meets physical-property specifications for aviation fuels. In the present analysis, an attempt has been made to show how performance charts can be prepared for ternary blends in which each of the components has been isopentanized to a Reid vapor pressure of 7 pounds per square inch.

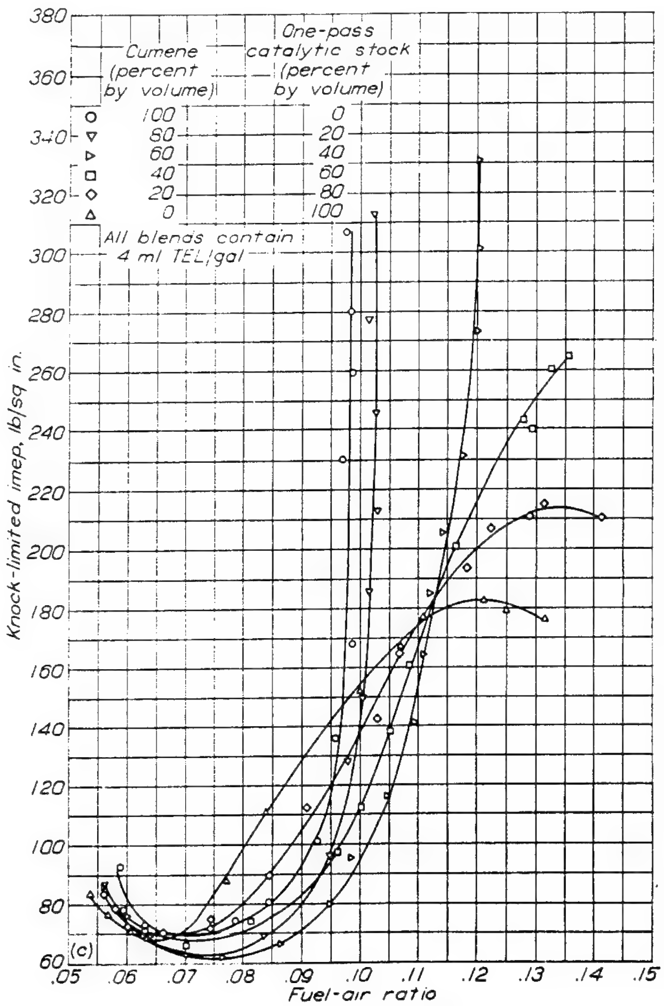


(a) Blends with virgin base stock.



(b) Blends with aviation alkylate.

FIGURE 9.—Knock-limited performance of binary blends of cumene with aviation alkylate, virgin base stock, and one-pass catalytic stock as determined in F–4 rating engine.



(c) Blends with one-pass catalytic stock.

FIGURE 9.—Concluded. Knock-limited performance of binary blends of cumene with aviation alkylate, virgin base stock, and one-pass catalytic stock as determined in F-4 rating engine.

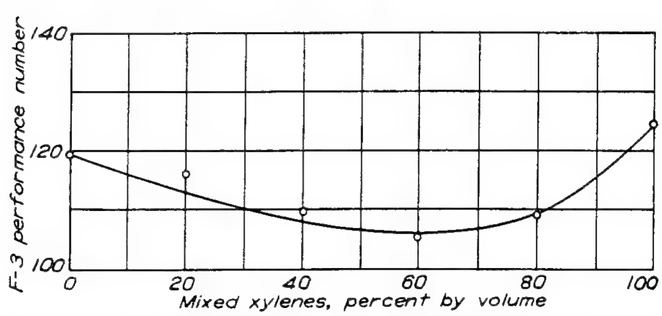


FIGURE 10.—Knock-limited performance determined by F-3 rating method for binary blends of mixed xylenes with aviation alkylate.

The addition of isopentane to adjust the vapor pressure of the components in a system such as that shown in figure 7 (a) will necessarily affect the maximum knock-free power attainable because of the performance rating of isopentane relative to the ratings of the other components in the system. (See table II.) In figure 7 (a), for example, a blend of 58.5-percent triptane, 30.5-percent alkylate, and 11-percent virgin base stock has a lean-rich performance-number rating of 135/200 and a Reid vapor pressure of approximately 3.5 pounds per square inch (estimated from table II). In order to obtain the same performance (135/200) with a blend of triptane, alkylate, and virgin base stock that has been isopentanized to a Reid vapor pressure of 7 pounds per square inch (maximum from specification), a blend of 55-percent triptane, 17-percent alkylate, 7-percent virgin base stock, and 21-percent isopentane could be used. The addition of isopentane has thus effectively decreased the quantity of triptane needed to obtain the 135/200 performance rating, which is attributed to the fact that isopentane has better performance characteristics than the alkylate or the virgin base stock used as well as a higher Reid vapor pressure than the other three constituents in the blend. (See table II.)

It must be emphasized that the preceding example is merely given as a sample consideration of a fuel characteristic other than knock that must be considered for a finished fuel blend. This example is not intended to imply that the preparation of fuel blends as presented herein with Reid vapor pressures adjusted to meet specifications will necessarily produce blends that will meet all pertinent specifications.

Several performance charts for quaternary blends containing isopentane were prepared for comparison with the charts previously described for ternary blends. In each of the quaternary systems, the vapor pressure was adjusted to 7 pounds per square inch. Three assumptions were made in the preparation of these charts:

(1) The relation between composition (volume basis) and Reid vapor pressure for binary blends of isopentane with another paraffinic fuel is linear.

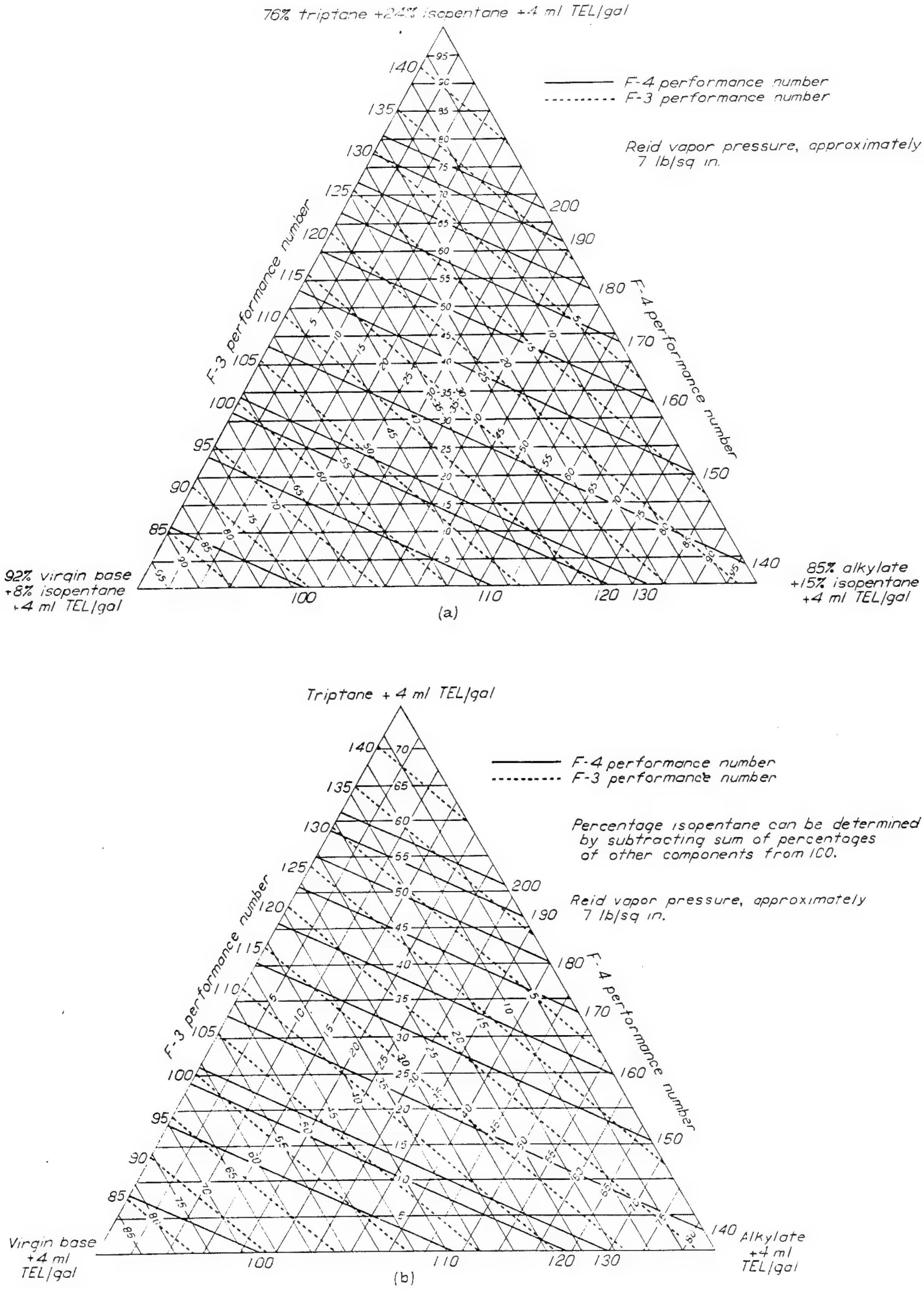
(2) The relation between composition and the reciprocal of F-4 (rich) knock-limited indicated mean effective pressure for binary blends of isopentane with another paraffinic fuel is linear.

(3) The relation between composition and F-3 performance number for binary blends of isopentane with another paraffinic fuel is linear.

On the basis of the available data, assumption (3) appears to be valid for only a few cases. For this reason the F-3 performance lines on the charts for quaternary blends may be in error.

As an example of the preparation of the performance chart for a quaternary system, it is assumed desirable to isopentanize the blends represented by figure 7 (a). The first step in this problem is to determine the amount of isopentane to be added to each of the pure components (fig. 7 (a)) to obtain a Reid vapor pressure of 7 pounds per square inch and to determine the resultant F-3 and F-4 performance-number ratings for these blends. This information was obtained from the foregoing assumptions and the data in table II and is presented in the following table:

	F-3 performance number	F-4 indicated mean effective pressure (lb/sq in.)
76% triptane + 24% isopentane + 4 ml TEL/gal	145	455
85% alkylate + 15% isopentane + 4 ml TEL/gal	121	200
92% virgin base + 8% isopentane + 4 ml TEL/gal	78	142



(a) Plain triangular coordinate.

(b) Triangular coordinate adjusted to show blend composition in terms of concentrations of individual constituents.

FIGURE 11.—Knock-limited performance determined by F-3 and F-4 rating methods for quaternary blends containing triptane, aviation alkylate, virgin base stock, and isopentane. F-4 ratings at fuel-air ratio of 0.11.

The triangular chart shown in figure 11 (a) was obtained by treating these three blends (all of which have Reid vapor pressures of 7 lb/sq in.) as separate components by the procedure used in preparing figure 7 (a). Any point on figure 11 (a) represents the F–3 and F–4 performance number of a quaternary blend. The actual quantity of each component in the blend, however, cannot be readily determined from the chart because the percentages given on the altitudes of the triangle show only the amounts of the binary blends at the vertexes. For this reason, the grid of the chart was so adjusted, as shown in figure 11 (b), that the quantity of any one of the four components in the blend could be determined from the chart.

As an example of the method of determining the composition of fuel in figure 11 (b), it is assumed that a blend of triptane, aviation alkylate, virgin base stock, and isopentane having a lean-rich rating of 130/180 is desired. The concentrations of triptane, alkylate, and virgin base stock in the blend having the desired rating can be read directly from the altitudes of the triangle in the manner used in previous charts. These concentrations are 48, 19, and 13 percent, respectively. The concentration of isopentane can be determined by subtracting the sum of the percentages of the other components from 100.

Performance charts for the following quaternary systems have been prepared and are presented in figure 12:

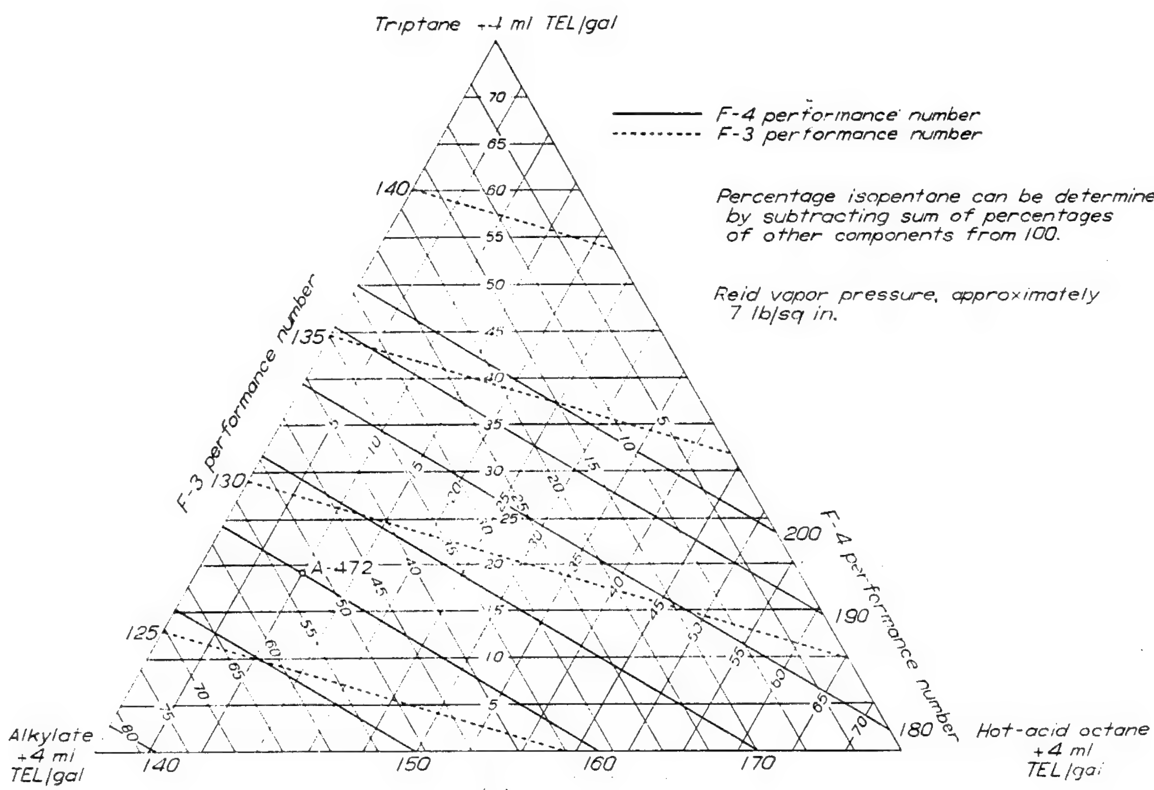
- Triptane, hot-acid octane, aviation alkylate, and isopentane
- Triptane, diisopropyl, aviation alkylate, and isopentane
- Triptane, diisopropyl, hot-acid octane, and isopentane
- Diisopropyl, hot-acid octane, aviation alkylate, and isopentane

The vapor pressure determined for the diisopropyl used in figure 12 was 7.4 pounds per square inch. (See table II.) In the preparation of figure 12, however, a vapor pressure of 7 pounds per square inch was assumed for diisopropyl.

ACCURACY OF PERFORMANCE CHARTS

The accuracy of the charts was determined by selecting ternary or quaternary blends from the various charts and investigating these blends by the standard F–3 and F–4 procedures. Inasmuch as the F–4 ratings shown on the charts were estimated at a fuel-air ratio of 0.11, the check ratings were determined at this same fuel-air ratio.

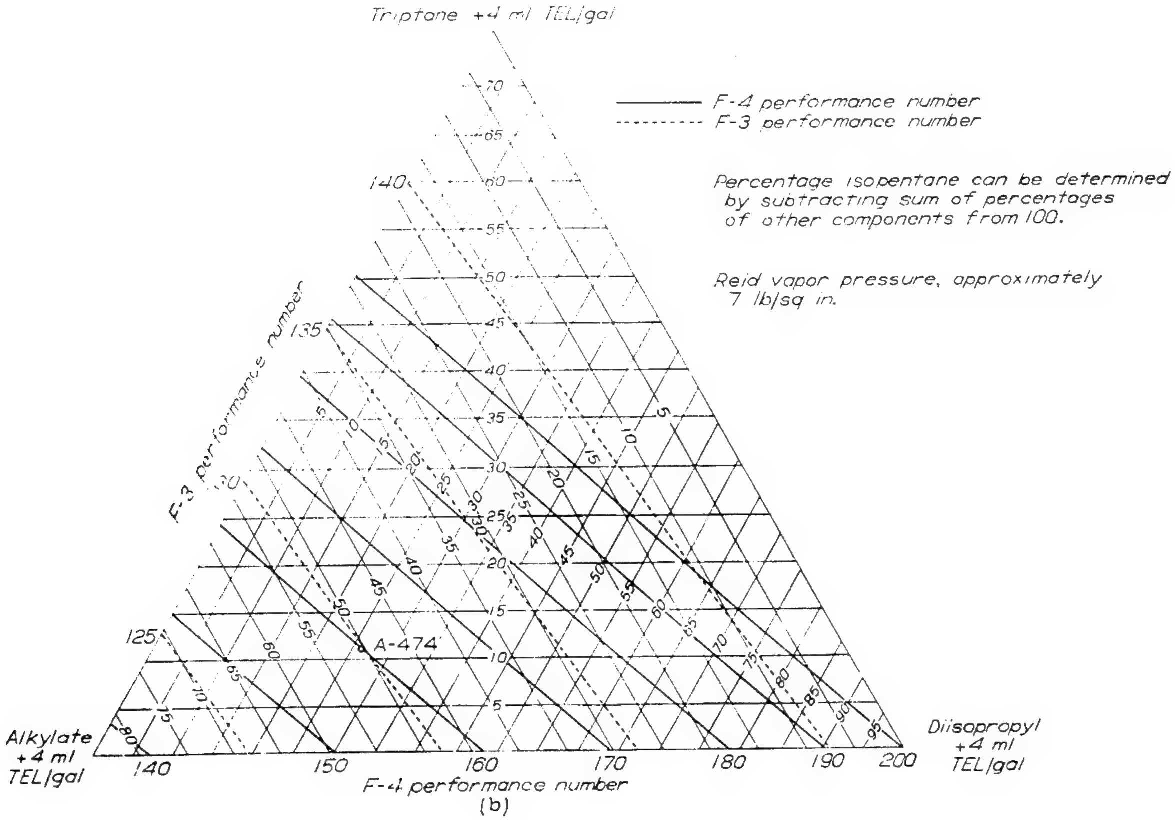
The check blends investigated and their ratings are shown in table III. These blends are also shown on the various charts by the symbols. The fuel numbers shown adjacent to each of the symbols on the charts correspond to the fuel numbers given in this table. All the data in table III are presented in figure 13 to show the relation between estimated and observed performance numbers. For the 25 blends shown in figure 13, the average deviation from the match line was 3.1 performance numbers for the F–3 ratings and 1.5 for the F–4 ratings.



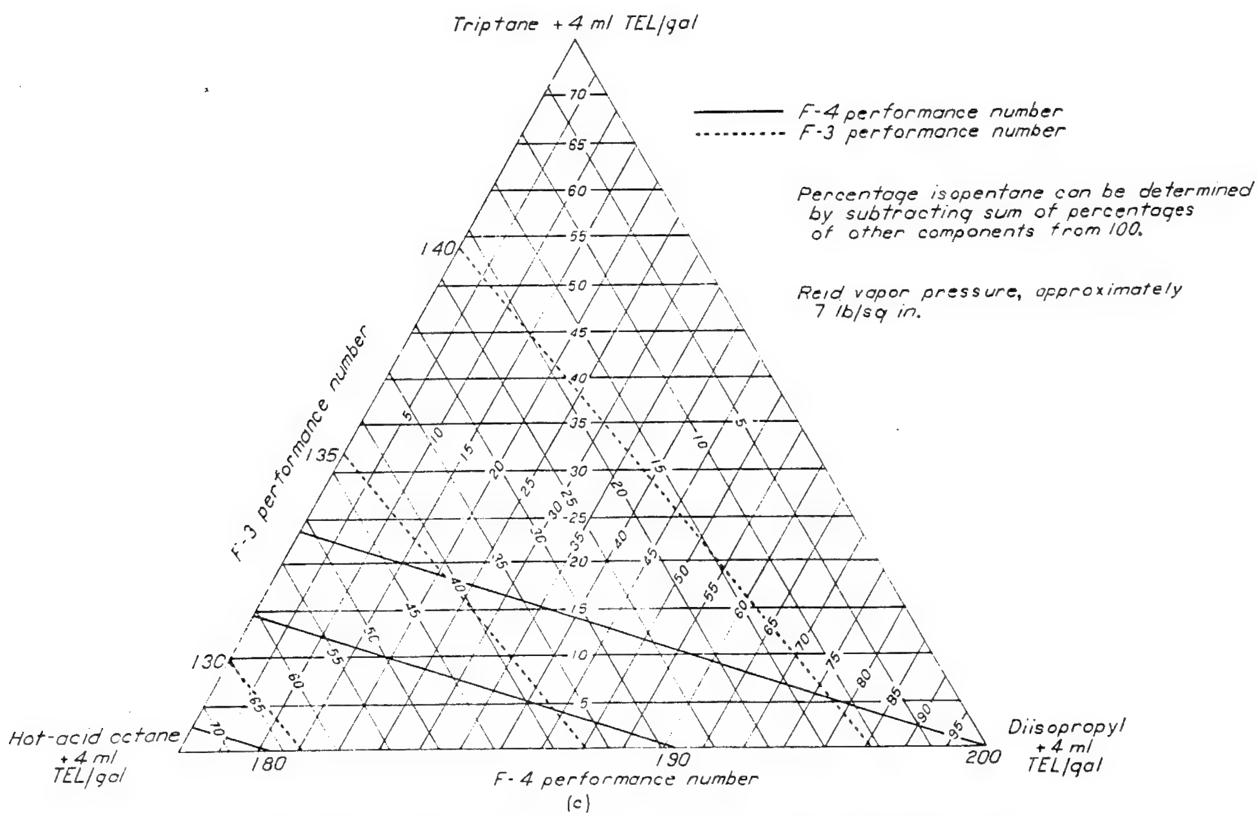
(a)

(a) Blends of triptane, hot-acid octane, aviation alkylate, and isopentane; F–4 ratings at fuel-air ratio of 0.11.

FIGURE 12.—Knock-limited performance determined by F–3 and F–4 rating methods for quaternary blends.



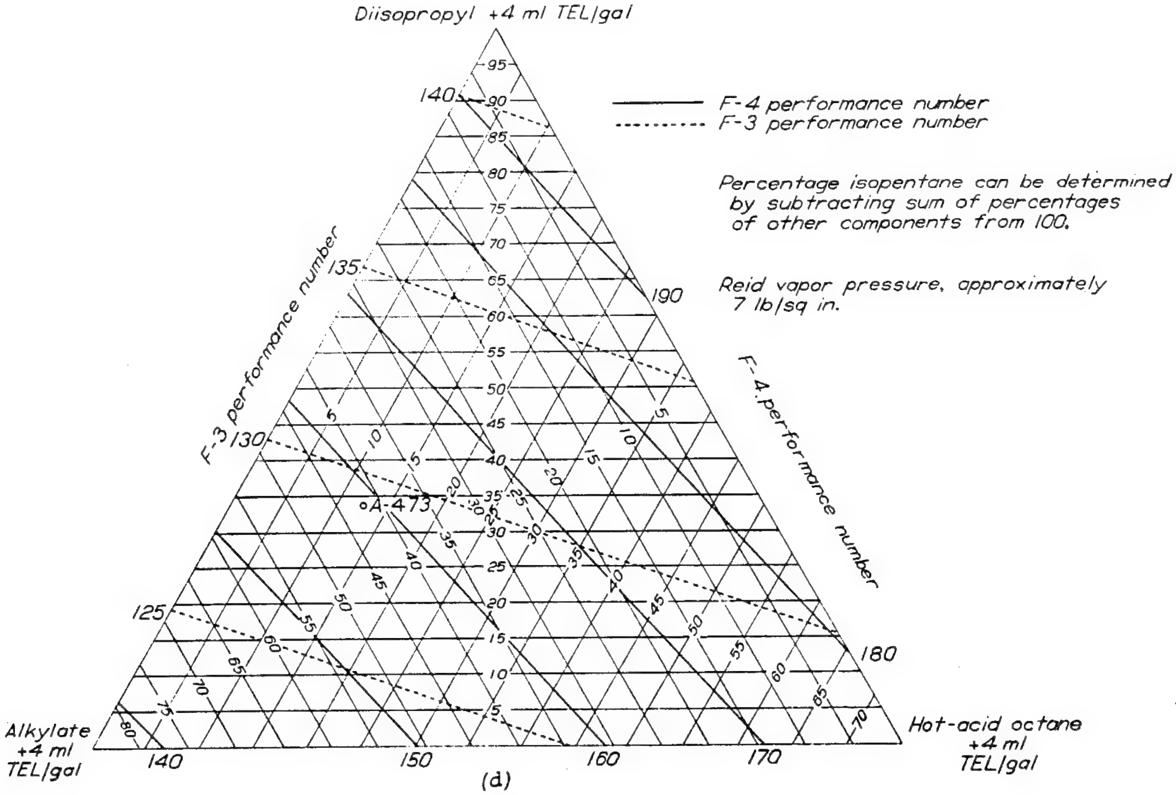
(b)



(c)

(b) Blends of triptane, diisopropyl, aviation alkylate, and isopentane; F-4 ratings at fuel-air ratio of 0.11.
(c) Blends of triptane, diisopropyl, hot-acid octane, and isopentane; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 12.—Continued. Knock-limited performance determined by F-3 and F-4 rating methods for quaternary blends.



(d) Blends of diisopropyl, hot-acid octane, aviation alkylate, and isopentane; F-4 ratings at fuel-air ratio of 0.11.

FIGURE 12.—Concluded. Knock-limited performance determined by F-3 and F-4 rating methods for quaternary blends.

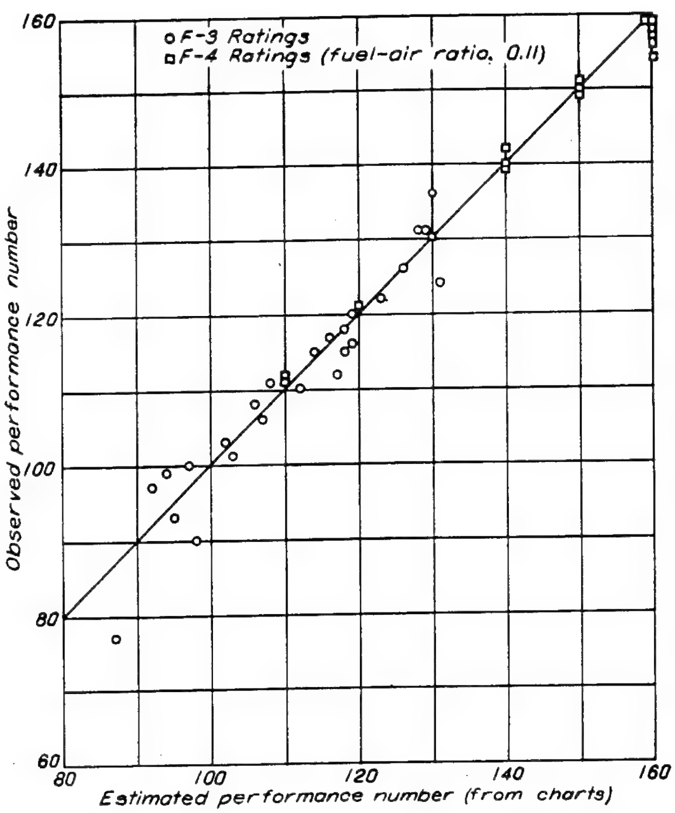


FIGURE 13.—Relation between estimated and observed knock-limited performance ratings as determined by F-3 and F-4 rating methods.

In consideration of the accuracy of the charts it must be emphasized that the previously mentioned discrepancies noted in the F-3 ratings of binary blends containing aromatics are responsible for some of the large deviations in table III. For this reason the F-3 performance lines for the aromatic systems shown in figures 7 and 8 must be used with considerable caution.

DISCUSSION OF PERFORMANCE CHARTS

The data in figures 7 and 8 can be used for certain general comparisons of paraffins, aromatics, and ethers. In figure 7 (a), for example, at the point representing a blend of 81-percent aviation alkylate, 19-percent virgin base stock, and 4 ml TEL per gallon, the lean-rich rating is 110/123. Moving on a straight line from this point toward the triptane vertex until 20-percent triptane has been added results in a blend having a rating of 118/145. The addition of 20-percent triptane to the base blend has thus increased the lean rating of the base blend by 8 performance numbers and the rich rating by 22.

On the other hand, if in figure 7 (e) 20-percent benzene is added to the same base blend used in the foregoing example, then the rating changes from 110/123 to 106/146. The addition of 20-percent benzene has decreased the lean rating by 4 performance numbers, whereas the rich rating has been increased by 23.

From this comparison, it follows that in the illustrative example the aromatic (benzene) and the paraffin (triptane) are equally effective for increasing the F-4 (rich) performance

but that triptane is more effective than benzene for improving lean performance.

When any two of the charts in figure 7 or 8 are compared, the nearer a given constant performance line is to the base of the triangle, the better the performance of the fuel represented by the top vertex of the triangle. For example, in figure 7 (a) the line representing an F-4 performance number of 200 is much nearer the base of the triangle than the same line in figure 7 (b). Triptane plus 4 ml TEL per gallon has therefore a higher rating than diisopropyl plus 4 ml TEL per gallon.

Observations similar to those made in the foregoing discussion can be made for the charts in figures 11 and 12. In the case of these figures, however, the effect of a single component cannot be isolated from the other components because the concentration of isopentane varies with that of any other component in the system.

SUMMARY OF RESULTS

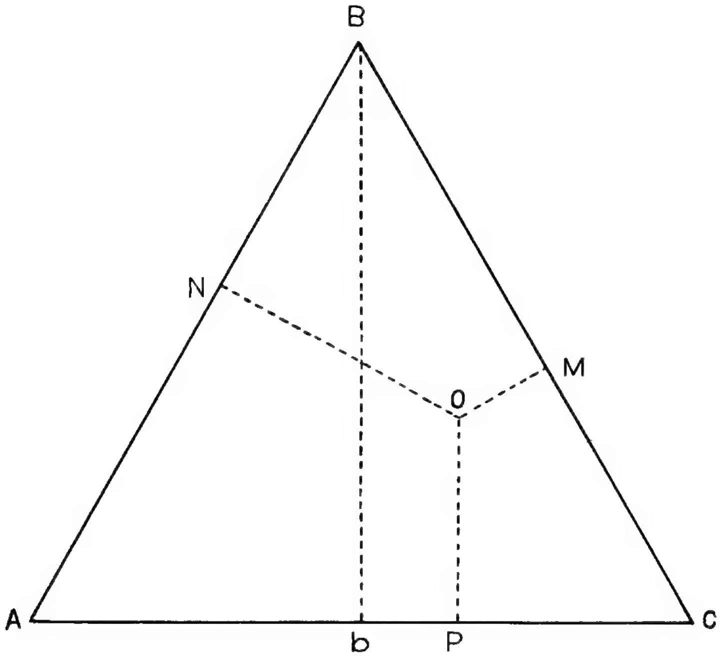
Charts are presented that permit the estimation of F-3 and F-4 knock-limited performance ratings for certain ternary and quaternary fuel blends. Ratings for various ternary and quaternary blends estimated from these charts compare favorably with experimental F-3 and F-4 ratings. Because of the unusual behavior of some of the aromatic blends in the F-3 engine, the charts for aromatic-paraffinic blends are probably less accurate than the charts for purely paraffinic blends.

AIRCRAFT ENGINE RESEARCH LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
CLEVELAND, OHIO, *January 29, 1945.*

APPENDIX

USE OF TRIANGULAR COORDINATE PAPER

The use of triangular coordinate paper to represent composition for a three-component system will be greatly simplified if it is remembered that for any point in an equilateral triangle the sum of the perpendiculars from that point to each of the sides is equal to the altitude of the triangle. For example, in the following diagram OP+OM+ON=Bb.



If each of the vertexes of the triangle represent 100 percent of one of the three constituents, then the percentage of component A in blend O is OM, the percentage of the component B is OP, and the percentage of component C is ON.

The equation of a straight line on triangular coordinate paper is of the form

$$a=bN_1+cN_2+N_3$$

where

a, b, c constants

N_1, N_2, N_3 concentration of components 1, 2, and 3 in ternary blend

Any equation relating knock-limited performance and blend composition that can be reduced to this form can be represented by a straight line of constant performance on triangular coordinate paper. Equation (1) presented in the text of this report can be reduced to this form by multiplying through by any one of the performance values $(\text{imep})_1$, $(\text{imep})_2$, or $(\text{imep})_3$.

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2. Sanders, Newell D.: A Method of Estimating the Knock Rating of Hydrocarbon Fuel Blends. NACA Rep. No. 760, 1943.
3. Sherwood, Thomas K., and Reed, Charles E.: Applied Mathematics in Chemical Engineering. McGraw-Hill Book Co., Inc., 1939, pp. 300–303.
4. Sanders, Newell D., Hensley, Reece V., and Breitwieser, Roland: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. I—Preliminary Tests in an Air-Cooled Cylinder. NACA ARR No. E4I28, 1944.
5. Wear, Jerrold D., and Sanders, Newell D.: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. II—Investigation of Leaded Paraffinic Fuels in an Air-Cooled Cylinder. NACA TN No. 1374, 1947.

TABLE I.—PERFORMANCE RATINGS OBTAINED IN F-3 AND F-4 ENGINES

[For each fuel there are three rows of values: The first row is imep, lb/sq in.; the second row for F-3 ratings is octane number or tetraethyl lead in S-3 reference fuel, ml/gal; the second row for F-4 ratings is percentage S-3 reference fuel in M-4 reference fuel or tetraethyl lead in S-3 reference fuel, ml/gal; the third row is performance number. The following abbreviations are used throughout the table: VBS for virgin base stock; alkylate for aviation alkylate; one-pass stock for one-pass catalytic stock; and MTB ether for methyl *tert*-butyl ether.]

Fuel	Fuel composition [a] (by volume)	F-3 ratings	F-4 ratings [b] Fuel-air ratio 0.065	0.070	0.085	0.095	0.100	0.110
A-355	VBS	-----	73	83	122	137	141	143
		90.7	96.6	99.8	0.08	99.8	99.0	97.8
		75	91	99	103	99	97	94
A-118	50% alkylate+50% VBS	-----	86	99	143	159	162	165
		98.8	0.10	0.19	0.34	0.33	0.29	0.24
		96	104	107	111	111	110	109
A-356	Alkylate	-----	104	129	176	190	195	201
		0.64	0.55	0.93	1.57	1.71	1.87	2.14
		119	117	124	134	135	137	140
A-132	30% one-pass stock+70% VBS	-----	72	71	116	130	136	145
		90.6	93.8	90.0	100	98.0	97.5	97.7
		75	84	78	100	94	94	94
A-116	50% one-pass stock+50% VBS	-----	64	76	116	137	145	156
		90.9	88.6	93.1	100	0.01	0.01	0.06
		76	76	84	100	101	101	103
A-119	80% one-pass stock+20% VBS	-----	67	76	114	142	154	165
		92.7	90.6	93.1	99.2	0.09	0.16	0.24
		79	78	84	97	104	106	109
A-122	30% one-pass stock+70% alkylate	-----	82	103	152	172	178	182
		0.15	100	0.26	0.45	0.58	0.75	0.83
		106	100	110	114	117	121	123
A-117	50% one-pass stock+50% alkylate	-----	76	91	143	167	176	186
		100	96.3	0.06	0.34	0.44	0.58	1.17
		100	91	103	111	114	117	129
A-121	80% one-pass stock+20% alkylate	-----	72	79	123	149	160	177
		96.3	93.8	95	0.09	0.19	0.26	0.48
		88	84	96	104	107	110	115
A-410	One-pass stock	-----	73	83	125	151	164	179
		93.4	96.6	99.8	0.12	0.16	0.28	0.49
		81	91	99	105	106	110	115
A-136	20% triptane+80% VBS	-----	74	90	134	155	162	167
		94.2	95.0	0.05	0.23	0.27	0.27	0.28
		83	88	102	108	110	110	110
A-137	40% triptane+60% VBS	-----	100	119	164	191	201	205
		0.18	0.43	0.55	0.96	1.75	2.07	2.07
		107	114	117	125	136	139	139
A-138	60% triptane+40% VBS	-----	117	142	224	260	264	269
		0.67	1.20	1.58	5.54	----	----	----
		120	129	134	160	175	175	175
A-272	20% triptane+80% alkylate	-----	90	126	185	213	225	237
		1.08	0.19	0.88	2.13	3.17	3.79	4.57
		127	106	123	140	148	152	156
A-273	40% triptane+60% alkylate	-----	98	126	225	262	274	283
		2.43	0.38	0.88	5.69	----	----	----
		142	113	123	160	177	182	184
A-274	60% triptane+40% alkylate	-----	111	159	275	316	326	334
		2.70	0.90	2.76	----	----	----	----
		145	124	145	195	213	216	218
A-275	80% triptane+20% alkylate	-----	139	190	314	----	----	----
		3.06	2.59	5.90	----	----	----	----
		147	144	161	----	----	----	----
A-276	20% triptane+80% one-pass stock [c]	----	66	72	117	146	160	186
		98.8	90.0	90.7	0.01	0.14	0.26	1.17
		96	77	78	101	105	110	135
A-277	40% triptane+60% one-pass stock [c]	----	81	89	139	176	195	231
		0.08	99.4	0.05	0.29	0.88	1.77	3.86
		103	99	101	111	124	136	152
A-278	60% triptane+40% one-pass stock [c]	----	100	109	171	218	244	291
		0.48	0.43	0.36	1.36	3.52	----	----
		115	114	113	131	150	162	190
A-279	80% triptane+20% one-pass stock [c]	---	126	147	290	361	391	----
		1.80	1.63	1.82	----	----	----	----
		136	134	137	----	----	----	----
A-271	Triptane [c]	----	204	262	[d]393	----	----	----
		3.30	----	----	----	----	----	----
		149	191	----	----	----	----	----
A-397	20% diisopropyl+80% VBS	----	77	91	132	149	154	155
		96.6	96.9	0.08	0.20	0.19	0.16	0.04
		90	91	103	108	107	106	101
A-398	40% diisopropyl+60% VBS	----	81	96	143	167	175	180
		0.09	99.4	0.16	0.34	0.44	0.50	0.67
		103	98	106	112	114	116	120
A-399	60% diisopropyl+40% VBS	----	96	108	163	187	197	207
		0.33	0.33	0.34	0.90	1.55	1.86	2.21
		111	111	112	124	134	137	141
A-400	80% diisopropyl+20% VBS	----	111	141	202	226	236	250
		1.17	1.10	1.56	3.23	4.14	5.07	-----
		128	127	134	148	153	158	163
A-405	20% diisopropyl+80% alkylate	----	125	146	192	210	217	222
		0.90	1.78	1.78	2.58	2.97	3.21	3.24
		124	136	136	144	146	148	148
A-406	40% diisopropyl+60% alkylate	----	138	158	206	227	234	240
		1.45	2.47	2.67	3.49	4.29	4.80	5.00
		132	143	144	150	154	156	157
A-407	60% diisopropyl+40% alkylate	----	132	154	212	240	252	263
		1.40	1.91	2.29	3.87	----	----	----
		132	138	141	152	162	167	171
A-408	80% diisopropyl+20% alkylate	----	136	162	226	261	275	292
		2.10	2.24	3.05	5.85	----	----	----
		139	141	147	161	176	182	190
A-401	20% diisopropyl+80% one-pass stock	----	79	89	132	163	177	195
		96.1	98.1	0.05	0.20	0.39	0.67	1.60
		88	95	102	108	113	120	134
A-402	40% diisopropyl+60% one-pass stock	----	84	99	150	177	189	209
		0.06	0.05	0.20	0.43	0.95	1.48	2.34
		102	102	108	114	125	133	142
A-403	60% diisopropyl+40% one-pass stock	---	96	114	165	196	210	235
		0.24	0.33	0.44	1.02	2.00	2.72	4.29
		108	111	114	126	138	145	154
A-404	80% diisopropyl+20% one-pass stock	----	120	143	197	229	245	272
		0.68	1.34	1.65	2.90	4.57	----	----
		120	131	135	146	155	162	177
A-393	Diisopropyl [c]	----	147	173	246	289	304	324
		2.41	3.53	4.11	----	-----	----	----
		142	150	153	175	195	-----	----
A-411	20% neohexane+80% VBS	----	74	86	124	142	147	150
		94.5	95.0	100	0.10	0.09	0.05	99.2
		84	88	100	104	103	102	98
A-412	40% neohexane+60% VBS	----	81	97	138	158	164	167
		0.05	99.4	0.17	0.28	0.31	0.32	0.28
		102	98	106	110	111	111	110
A-413	60% neohexane+40% VBS	----	93	108	159	178	183	187
		0.36	0.26	0.34	0.67	1.03	1.17	1.25
		112	110	112	120	126	128	130
A-414	80% neohexane+20% VBS	----	108	130	182	203	208	210
		2.00	0.75	1.06	1.95	2.48	2.57	2.41
		138	121	127	138	143	143	142
A-415	20% neohexane+80% alkylate	----	112	130	172	193	199	202
		1.10	0.95	1.06	1.41	1.85	1.95	1.91
		127	125	127	132	137	138	138
A-416	40% neohexane+60% alkylate	----	118	137	186	203	207	209
		1.50	1.25	1.38	2.19	2.48	2.50	2.35
		133	130	131	140	143	143	142
A-417	60% neohexane+40% alkylate	----	124	146	195	212	215	216
		2.57	1.53	1.78	2.78	3.10	3.07	2.83
		143	133	136	145	147	147	145
A-418	80% neohexane+20% alkylate	----	137	158	208	224	227	226
		3.36	2.35	2.67	3.61	3.93	3.93	3.52
		149	142	144	151	152	152	150
A-420	20% neohexane+80% one-pass stock	----	79	95	146	171	180	190
		96.6	98.1	0.14	0.38	0.50	0.92	1.38
		90	95	105	113	116	124	131
A-421	40% neohexane+60% one-pass stock	----	86	107	165	190	197	203
		0.10	0.10	0.33	1.02	1.70	1.86	1.96
		104	104	111	126	135	137	138
A-422	60% neohexane+40% one-pass stock	----	108	138	192	210	215	217
		0.33	0.75	1.43	2.58	2.97	3.07	2.90
		111	121	132	143	146	147	146
A-423	80% neohexane+20% one-pass stock	----	132	162	214	230	233	234
		1.66	1.91	3.05	4.00	4.72	4.67	4.14
		135	138	147	153	156	156	153
A-394	Neohexane [f]	----	159	187	230	240	242	243
		6.00	4.76	5.58	---	---	5.87	5.43
		161	156	160	163	162	161	159
A-123	20% isopentane+80% VBS	----	72	87	127	141	146	149
		94.4	93.8	0.02	0.14	0.07	0.03	98.9
		83	84	101	106	103	101	99
A-124	40% isopentane+60% VBS	----	80	99	139	151	155	159
		99.1	98.8	0.20	0.29	0.21	0.18	0.12
		97	96	108	110	108	107	105
A-134	60% isopentane+40% VBS	----	87	112	153	168	172	174
		0.23	0.12	0.41	0.46	0.46	0.45	0.42
		108	105	114	114	114	114	113
A-375	20% isopentane+80% alkylate	----	121	144	186	201	204	204
		0.92	1.39	1.69	2.19	2.34	2.29	2.00
		124	131	135	140	142	141	138
A-376	40% isopentane+60% alkylate	----	121	144	191	203	205	204
		0.99	1.39	1.69	2.52	2.48	2.36	2.00
		125	131	135	143	143	142	138
A-388	20% isopentane+80% one-pass stock	----	78	87	132	160	173	188
		95.8	97.5	0.02	0.20	0.34	0.47	1.29
		87	94	101	108	111	115	130
A-389	40% isopentane+60% one-pass stock	----	85	97	140	168	180	192
		100	0.07	0.17	0.30	0.46	0.92	1.47
		100	103	107	111	115	124	133
A-139	20% hot-acid octane+80% VBS	----	70	83	128	147	151	154
		94.3	92.5	98.0	0.15	0.16	0.11	0.02
		83	83	94	106	106	105	101
A-140	40% hot-acid octane+60% VBS	----	74	89	143	168	173	179
		100	95.0	0.03	0.34	0.46	0.47	0.58
		100	94	101	111	114	115	117
A-141	60% hot-acid octane+40% VBS	----	84	106	165	191	198	207
		0.18	0.05	0.31	1.02	1.75	1.91	2.21
		107	102	111	126	136	138	140
A-367	20% hot-acid octane+80% alkylate	----	121	142	188	205	210	215
		0.82	1.39	1.60	2.32	2.62	2.72	2.76
		123	131	134	141	144	145	145
A-368	40% hot-acid octane+60% alkylate	----	125	148	200	219	226	235
		0.72	1.58	1.87	3.10	3.59	3.86	4.29
		121	134	137	147	150	152	154
A-369	60% hot-acid octane+40% alkylate	----	129	154	216	240	248	257
		0.88	1.77	2.29	4.31	---	---	---
		124	136	141	154	162	164	168
A-370	80% hot-acid octane+20% alkylate	----	129	154	238	269	276	280
		0.72	1.77	2.29	---	---	---	---
		121	136	141	169	182	183	182
A-371	20% hot-acid octane+80% one-pass stock	----	80	90	138	170	185	206
		95.1	98.8	0.06	0.28	0.49	1.30	2.14
		86	95	102	110	115	130	140
A-372	40% hot-acid octane+60% one-pass stock	----	88	97	154	192	208	229
		100	0.14	0.17	0.48	1.80	2.57	3.73
		100	105	107	115	136	143	151

[a] Each fuel contains approximately 4 ml TEL/gal.
[b] Based on fixed reference-fuel framework (reference 1).
[c] Knock-limited performance of engine with one-pass catalytic stock was low on day fuels were investigated.
[d] Estimated value.
[e] Values for knock-limited imep were averaged from three curves.
[f] Values for knock-limited imep were averaged from two curves.

TABLE I—PERFORMANCE RATINGS OBTAINED IN F-3 AND F-4 ENGINES—Concluded

Fuel	Fuel composition [a] (by volume)	F-3 ratings	F-4 ratings [b], Fuel-air ratio 0.065	0.070	0.085	0.095	0.100	0.110
A-373	60% hot-acid octane+40% one-pass stock	----	90	101	164	203	220	215
		0.18	0.19	0.23	0.96	2.48	3.43	5.71
		107	107	108	125	143	149	160
A-374	80% hot-acid octane+20% one-pass stock	----	99	115	187	224	240	268
		0.45	0.41	0.45	2.26	3.93	5.60	--
		115	114	115	141	152	160	175
A-330	Hot-acid octane [f]	----	131	159	250	289	304	317
		1.08	1.86	2.76	----	----	----	----
		127	137	145	178	195	----	----
A-257	20% mixed xylenes+80% VBS	----	68	78	114	132	138	148
		92.6	91.3	94.7	99.2	98.7	98.1	98.6
		79	79	86	97	96	94	96
A-258	40% mixed xylenes+60% VBS	----	69	78	117	147	160	182
		95.5	91.9	94.7	0.03	0.16	0.26	0.83
		86	80	86	101	106	110	123
A-259	60% mixed xylenes+40% VBS	----	74	85	146	194	216	253
		95.2	95.0	99.3	0.38	1.90	3.14	----
		86	87	99	113	137	148	165
A-260	80% mixed xylenes+20% VBS	----	84	95	214	----	----	----
		0.04	0.05	0.14	4.00	----	----	----
		101	102	105	153	----	----	----
A-261	20% mixed xylenes+80% alkylate	----	88	101	158	194	208	227
		0.52	0.14	0.23	0.65	1.90	2.57	3.59
		116	105	108	119	137	143	150
A-262	40% mixed xylenes+60% alkylate	----	82	95	153	206	252	287
		0.27	100	0.14	0.46	2.69	----	----
		110	100	105	115	144	167	187
A-263	60% mixed xylenes+40% alkylate	----	85	98	181	274	----	----
		0.14	0.07	0.19	1.89	--	----	----
		105	103	107	137	185	----	----
A-264	80% mixed xylenes+20% alkylate	----	87	103	260	336	370	----
		0.27	0.12	0.27	----	----	----	----
		110	105	110	185	----	----	----
A-265	20% mixed xylenes+80% one-pass stock [c]	----	71	74	111	138	151	178
		94.7	93.1	92.0	97.9	0.03	0.11	0.50
		84	83	81	94	101	105	116
A-266	40% mixed xylenes+60% one-pass stock [c]	----	80	86	133	172	196	246
		97.5	98.8	100	0.21	0.58	1.81	5.86
		92	95	100	108	118	136	161
A-267	60% mixed xylenes+40% one-pass stock [c]	----	95	100	184	251	282	339
		98.8	0.31	0.22	2.06	----	----	----
		96	111	108	139	169	187	----
A-268	80% mixed xylenes+20% one-pass stock [c]	----	102	106	351	----	----	----
		0.16	0.48	0.31	----	----	----	----
		106	115	111	----	----	----	----
A-256	Mixed xylenes [c,e]	----	105	122	----	----	----	----
		0.92	0.60	0.69	----	----	----	----
		124	118	120	----	----	----	----
A-245	20% cumene+80% VBS	----	67	72	98	123	134	154
		92.4	90.6	90.7	92.5	95.7	96.9	0.02
		78	78	78	82	88	91	101
A-244	40% cumene+60% VBS	----	67	70	95	117	130	160
		92.7	90.6	89.3	91.3	93.7	95.6	0.14
		79	78	76	80	84	88	105
A-246	60% cumene+40% VBS	----	67	72	94	118	132	174
		94.2	90.6	90.7	90.8	94.0	96.3	0.42
		83	78	78	78	85	91	114
A-247	80% cumene+20% VBS	----	77	76	90	120	151	----
		96.0	96.9	93.3	89.2	94.7	0.11	----
		88	91	84	76	86	105	----
A-248	20% cumene+80% alkylate	----	98	102	143	172	187	215
		0.32	0.38	0.25	0.34	0.58	1.39	2.76
		111	113	109	111	117	131	145
A-249	40% cumene+60% alkylate	----	71	76	113	148	171	233
		0.11	93.1	93.3	98.8	0.17	0.44	4.00
		105	84	84	95	106	114	153
A-250	60% cumene+40% alkylate	----	77	76	94	124	149	277
		0.03	96.9	93.3	90.8	96.0	0.08	----
		101	91	84	78	90	103	180
A-251	80% cumene+20% alkylate	----	74	73	86	114	160	----
		97.7	95.0	91.3	87.5	92.7	0.26	----
		93	87	80	73	82	110	----
A-252	20% cumene+80% one-pass stock	----	70	69	91	120	137	175
		93.0	92.5	88.6	89.6	94.3	97.8	0.44
		80	82	75	76	85	93	114
A-253	40% cumene+60% one-pass stock	----	70	67	75	95	112	168
		93.6	92.5	87.4	82.9	86.3	90.0	0.30
		82	82	74	67	72	77	111
A-254	60% cumene+40% one-pass stock	----	66	62	65	81	94	153
		93.0	90.0	84.0	78.8	81.3	84.4	100
		80	78	68	62	65	69	100
A-255	80% cumene+20% one-pass stock	----	66	63	70	98	141	----
		95.0	90.0	84.8	80.8	87.3	99.1	----
		85	78	69	64	74	98	----
A-240	Cumene [e]	----	77	75	87	122	----	----
		95.0	96.9	92.7	87.9	95.3	----	----
		85	91	83	74	88	----	----
A-341	20% benzene+80% VBS	----	78	85	134	155	162	168
		91.4	97.5	99.4	0.22	0.27	0.29	0.30
		76	93	97	108	110	110	111
A-342	40% benzene+60% VBS	----	81	89	146	178	190	208
		92.4	99.4	0.05	0.37	1.03	1.63	2.28
		78	97	102	112	126	134	141
A-343	60% benzene+40% VBS	----	78	85	244	346	384	----
		94.2	97.5	99.4	----	----	----	----
		83	93	97	173	----	----	----
A-344	80% benzene+20% VBS	----	98	115	----	----	----	----
		96.2	0.38	0.45	----	----	----	----
		88	113	115	----	----	----	----
A-358	20% benzene+80% alkylate	----	117	127	182	212	222	234
		0.43	1.20	0.92	1.95	3.10	3.57	4.14
		114	129	124	137	147	150	153
A-359	40% benzene+60% alkylate	----	102	112	182	230	253	295
		0.12	0.48	0.41	1.95	4.72	----	----
		105	115	114	137	156	168	192
A-360	60% benzene+40% alkylate	----	102	110	336	----	----	----
		100	0.48	0.38	----	----	----	----
		100	115	113	----	----	----	----
A-361	80% benzene+20% alkylate	----	119	178	----	----	----	----
		98.3	1.30	4.63	----	----	----	----
		94	130	156	----	----	----	----
A-362	20% benzene+80% one-pass stock	----	77	86	142	172	184	203
		93.8	96.9	100	0.33	0.58	1.25	1.96
		82	91	100	111	118	130	138
A-363	40% benzene+60% one-pass stock	----	82	79	160	213	238	264
		92.0	100	95.3	0.73	3.17	5.33	----
		78	100	88	121	148	159	172
A-364	60% benzene+40% one-pass stock	----	68	72	191	254	280	328
		91.5	91.3	90.7	2.52	----	----	----
		77	80	78	143	172	186	----
A-365	80% benzene+20% one-pass stock	----	94	93	----	----	----	----
		93.0	0.29	0.11	----	----	----	----
		80	110	105	----	----	----	----
A-340	Benzene [f]	----	199	----	----	----	----	----
		87	----	----	----	----	----	----
		68	186	196	----	----	----	----
A-321	20% toluene+80% VBS	----	85	96	137	156	164	172
		93.7	0.07	0.16	0.26	0.29	0.32	0.27
		82	103	106	110	110	111	110
A-322	40% toluene+60% VBS	----	92	96	175	228	245	266
		95.1	0.24	0.16	1.57	4.43	----	----
		85	109	106	134	155	162	173
A-323	60% toluene+40% VBS	----	88	95	204	303	346	425
		97.0	0.14	0.14	3.36	----	----	----
		91	105	105	149	----	----	----
A-324	80% toluene+20% VBS	----	101	113	340	----	----	----
		98.8	0.45	0.42	----	----	----	----
		96	115	114	----	----	----	----
A-325	20% toluene+80% alkylate	----	121	139	191	221	232	249
		0.48	1.39	1.47	2.52	3.73	4.53	----
		115	131	132	143	151	155	162
A-326	40% toluene+60% alkylate	----	108	128	223	275	308	348
		0.54	0.75	0.97	5.38	----	----	----
		116	121	125	159	186	----	----
A-327	60% toluene+40% alkylate	----	100	105	300	----	----	----
		0.25	0.43	0.30	----	----	----	----
		109	114	111	----	----	----	----
A-328	80% toluene+20% alkylate	----	108	116	----	----	----	----
		0.16	0.75	0.47	----	----	----	----
		106	121	115	----	----	----	----
A-331	20% toluene+80% one-pass stock	----	80	90	137	169	184	212
		95.1	98.8	0.06	0.26	0.47	1.25	2.55
		85	95	103	110	115	130	143
A-332	40% toluene+60% one-pass stock	----	85	92	151	202	224	262
		95.3	0.07	0.09	0.44	2.41	3.72	----
		86	103	103	114	142	151	171
A-333	60% toluene+40% one-pass stock	----	91	95	178	270	319	----
		97.4	0.21	0.14	1.73	----	----	----
		91	108	105	135	182	----	----
A-334	80% toluene+20% one-pass stock	----	102	106	----	----	----	----
		0.10	0.48	0.31	----	----	----	----
		104	115	111	----	----	----	----
A-320	Toluene [f]	----	134	140	----	----	----	----
		0.57	2.00	1.51	----	----	----	----
		118	138	133	----	----	----	----
A-336	20% MTB ether+80% VBS	----	95	101	144	170	179	187
		98.8	0.31	0.23	0.30	0.49	0.83	1.25
		96	111	108	111	115	121	130
A-337	40% MTB ether+60% VBS	----	112	113	165	204	223	253
		0.12	0.95	0.42	1.02	2.55	3.64	----
		105	125	114	126	143	151	165
A-338	60% MTB ether+40% VBS	----	192	163	228	281	307	355
		0.92	----	3.14	----	----	----	----
		124	180	148	162	190	----	----
A-339	80% MTB ether+20% VBS	----	----	239	309	379	----	----
		2.61	----	----	----	----	----	----
		144	----	----	----	----	----	----
A-347	20% MTB ether+80% alkylate	----	143	155	230	258	268	281
		1.68	3.06	2.38	----	----	----	----
		135	146	142	163	174	178	183
A-348	40% MTB ether+60% alkylate	----	166	174	258	312	338	377
		2.30	5.43	4.21	----	----	----	----
		141	159	154	183	----	----	----
A-349	60% MTB ether+40% alkylate	----	258	229	327	406	442	----
		2.50	----	----	----	----	----	----
		143	----	193	----	----	----	----
A-350	80% MTB ether+20% alkylate	----	307	271	374	----	----	----
		6.0	----	----	----	----	----	----
		161	----	----	----	----	----	----
A-351	20% MTB ether+80% one-pass stock	----	87	91	144	179	194	218
		96.1	0.12	0.08	0.35	1.10	1.72	2.97
		88	105	103	112	127	135	146
A-352	40% MTB ether+60% one-pass stock	----	113	112	163	204	225	269
		0.14	1.00	0.41	0.85	2.55	3.79	----
		105	126	114	123	143	152	175
A-353	60% MTB ether+40% one-pass stock	----	185	160	230	289	319	376
		0.47	----	2.86	----	----	----	----
		115	173	146	163	195	----	----
A-354	80% MTB ether+20% one-pass stock	----	269	237	301	370	----	----
		1.00	----	----	----	----	----	----
		126	----	200	----	----	----	----
A-335	MTB ether [f]	----	----	330	406	----	----	----
		>6.00	----	----	----	----	----	----
		>161	----	----	----	----	----	----

TABLE II—F-3 AND F-4 PERFORMANCE RATINGS AND REID VAPOR PRESSURES FOR VARIOUS AVIATION-FUEL COMPONENTS

Blending agent	Reid vapor pressure (lb/sq in.)	Performance number [a] F-3	Performance number [a] F-4 [b]
Isopentane	19.6	[c] 133	[c] 144
Neohexane	8.7	161	159
Methyl *tert*-butyl ether	8.8	>161	>200
Diisopropyl	7.4	142	202
Virgin base stock	5.9	73	94
Alkylate	4.7	119	137
Benzene	3.5	[d] 68	>200
Triptane	3.0	149	>200
Hot-acid octane	2.7	127	197
Toluene	1.1	118	>200
Mixed xylenes	.5	124	>200
Cumene	.3	85	>200

[a] Performance numbers are for pure blending agent containing 4 ml TEL/gal.
[b] Performance numbers over 161 are extrapolated (fig. 1). Ratings are for fuel-air ratio of 0.11.
[c] Extrapolated from experimental data for blends containing up to 60-percent isopentane.
[d] Assumed to be same as rating for unleaded benzene.

TABLE III—F-3 AND F-4 PERFORMANCE RATINGS OF TERNARY AND QUATERNARY FUEL BLENDS

[The following abbreviations are used throughout the table: VBS for virgin base stock; alkylate for aviation alkylate; one-pass stock for one-pass catalytic stock; and MTB ether for methyl *tert*-butyl ether.]

Figure	Fuel	Fuel composition [a] (by volume)	F-3 ratings Estimated	F-3 ratings Observed	F-4 ratings [b] Estimated	F-4 ratings [b] Observed
		Ternary blends				
6	A-477	59% hot-acid octane+25% VBS+16% alkylate	112	110	150	149
6	A-487	11% hot-acid octane+48% VBS+41% alkylate	98	90	110	111
7 (a)	A-233	20% triptane+5% VBS+74% alkylate	126	126	150	151
7 (a)	A-235	29% triptane+20% VBS+51% alkylate	119	120	150	151
7 (a)	A-234	38% triptane+35% VBS+27% alkylate	114	115	150	150
7 (a)	A-466	43% triptane+28% VBS+29% alkylate	119	116	160	158
7 (a)	A-481	12% triptane+14% VBS+74% alkylate	116	117	140	142
7 (a)	A-486	13% triptane+61% VBS+26% alkylate	95	93	110	112
7 (b)	A-478	43% diisopropyl+12% VBS+45% alkylate	123	122	150	150
7 (b)	A-524	34% diisopropyl+52% VBS+14% alkylate	103	101	120	121
7 (c)	A-483	56% neohexane+14% VBS+30% alkylate	131	124	140	140
7 (c)	A-523	12% neohexane+43% VBS+45% alkylate	102	103	110	111
7 (e)	A-482	23% benzene+34% VBS+43% alkylate	97	100	140	139
7 (e)	A-522	47% benzene+41% VBS+12% alkylate	87	77	160	154
7 (h)	A-484	14% toluene+54% VBS+32% aklylate	92	97	130	130
		Ternary blends—Concluded				
7 (h)	A-521	23% toluene+17% VBS+60% alkylate	107	106	160	156
7 (i)	A-520	33% MTB ether+55% VBS+12% alkylate	106	108	160	154
7 (i)	A-539	6% MTB ether+59% VBS+35% alkylate	94	99	110	111
8 (a)	A-470	55% hot-acid octane+13% one-pass stock+32% alkylate	118	118	160	159
8 (b)	A-471	35% triptane+45% one-pass stock+20% alkylate	108	111	160	159
8 (b)	A-480	20% triptane+16% one-pass stock+64% alkylate	117	112	150	150
8 (c)	A-555	39% diisopropyl+24% one-pass stock+37% alkylate	118	115	150	150
		Quaternary blends				
12 (a)	A-472	19% triptane+10% hot-acid octane+52.5% alkylate+18.5% isopentane	128	131	160	157
12 (b)	A-474	11.5% triptane+25.5% diisopropyl+50.5% alkylate+12.5% isopentane	130	136	160	159
12 (d)	A-473	34% diisopropyl+12.5% hot-acid octane+41.5% alkylate+12% isopentane	129	131	159	159

[a] Each fuel contains approximately 4 ml TEL/gal.
[b] F-4 ratings made at fuel-air ratio of 0.11.

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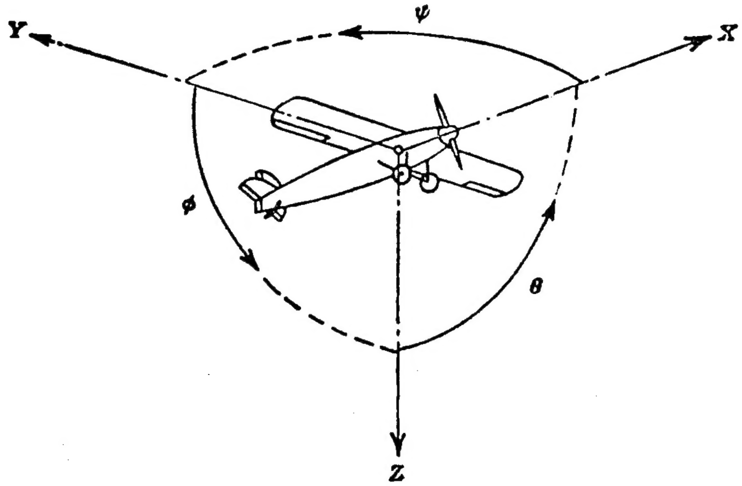

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\dfrac{L}{qbS}$ (rolling) $\quad C_m=\dfrac{M}{qcS}$ (pitching) $\quad C_n=\dfrac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

T Thrust, absolute coefficient $C_T=\dfrac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q=\dfrac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P=\dfrac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient$=\sqrt[5]{\dfrac{\rho V^5}{P n^2}}$

η Efficiency

n Revolutions per second, rps

Φ Effective helix angle$=\tan^{-1}\left(\dfrac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec

1 metric horsepower=0.9863 hp

1 mph=0.4470 mps

1 mps=2.2369 mph

1 lb=0.4536 kg

1 kg=2.2046 lb

1 mi=1,609.35 m=5,280 ft

1 m=3.2808 ft